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COMMISSION

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PIER COLLABORATIVE REPORT

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Preface

The California Air Resources Board (ARB) carries out and funds research to reduce the health, environmental, and economic impacts of indoor and outdoor air pollution in California. This research involves four general program areas:

- Health and Welfare Effects
- Exposure Assessment
- Technology Advancement and Pollution Prevention
- Global Air Pollution

For more information about the ARB Research Program, please see ARB's website at: www.arb.ca.gov/research/research.htm, or contact ARB's Research Division at (916) 445-0753. For more information about ARB's Indoor Exposure Assessment Program please visit the website at: www.arb.ca.gov/research/indoor/indoor.htm.

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

- PIER funding efforts are focused on the following RD&D program areas:
- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Ventilation and Indoor Air Quality in New Homes is the final report for project contract number 500-02-023, ARB contract number 04-310, conducted by Indoor Environmental Engineering. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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Abstract

Concerns have been raised regarding whether homeowners use windows, exhaust fans, and other mechanical ventilation devices enough to remove indoor air contaminants and excess moisture. In a multi-season study of ventilation and indoor air quality of 108 new single-family, detached homes in California, window use, ventilation rates, and air contaminant concentrations were measured. The median 24-hour outdoor air exchange rate was 0.26 air changes per hour; 67 percent of the homes were below the California building code requirement of 0.35 air changes per hour; and 32 percent of the homes did not use their windows. Home-to-garage pressure testing guidelines were exceeded in 65 percent of the homes. The median indoor formaldehyde concentration was 36 micrograms per cubic meter (range of 4.8 to 136 micrograms per cubic meter). Nearly all homes had formaldehyde concentrations that exceeded guidelines for cancer and chronic irritation, while 59 percent exceeded guidelines for acute irritation. In conclusion, new single-family detached homes in California are built relatively airtight, can have very low outdoor air exchange rates, and can often exceed exposure guidelines for air contaminants with indoor sources, such as formaldehyde and some other volatile organic compounds. Mechanical ventilation systems are needed to provide a dependable, continuous supply of outdoor air to new homes, and reductions of various indoor formaldehyde sources are also needed.

Keywords: air contaminant exposure guidelines, air exchange rate, carbon monoxide, building envelope tightness, exhaust fans, formaldehyde, garage air contaminants, indoor air contaminant emission rates, indoor air contaminant sources, indoor air quality, mechanical ventilation systems, natural ventilation, nitrogen dioxide, particulate matter, ventilation standards, volatile organic compounds, windows.

Executive Summary

Introduction and Purpose

Concerns have been raised regarding whether homeowners use windows, doors, exhaust fans, and other mechanical ventilation devices enough to remove indoor air contaminants and excess moisture. Building practices and building standards for energy efficiency have led to more tightly sealed homes that rely on occupants to open windows for ventilation. However, there is very little information on current ventilation practices, indoor air quality, or indoor air contaminant sources in homes. This study provides, for the first time, accurate and current statewide information on ventilation and indoor air quality in new California homes.

A mail survey conducted in 2005 on occupants' use of windows and mechanical ventilation equipment in 1,515 new single-family homes in California confirmed that many homeowners never use their windows for ventilation. From this mail survey, a concern emerged that the current California residential building code allowance for ventilation to be provided merely through openable windows may not be sufficient to enable new homes to receive adequate ventilation to control indoor air contaminants to acceptable levels.

As a follow-up to the mail survey, a large field study was then conducted to measure window and mechanical ventilation system use, outdoor air ventilation rates, sources and concentrations of indoor air contaminants, and occupant perceptions. Data on indoor air quality and household ventilation systems and practices were obtained from multiple seasons and regions of the state. Measured levels of ventilation and indoor air quality were compared to current guidelines and standards. These data will help characterize the full range of indoor air contaminant exposure in such homes. Information on the use of windows, fans, and central systems collected in this field study will help establish realistic values for developing California standards for building energy efficiency.

The Energy Commission used these study results to revise the state's 2008 Residential Building Energy Efficiency standards to require mechanical ventilation to provide more healthful homes in California. The study results will improve the California Air Resource Board's ability to identify current sources of indoor air contaminants, to assess Californians' current exposure to measured toxic air contaminants, and to recommend effective strategies for reducing indoor air pollution.

Methods

The field study design involved recruitment of single-family detached Californian homes built between 2002 and 2004, using the University of California at Berkeley mail survey database as well as some supplementary recruitment. The homes were occupied by owners for at least one year before testing occurred, and homes with occupants who smoked indoors were excluded. This field study involved 108 homes from Northern and Southern

California, including a subset of 26 homes with mechanical outdoor-air ventilation systems. Home age ranged from 1.7 years to 5.5 years. The field teams measured home ventilation and indoor contaminant source characteristics, including the amount of composite wood, indoor contaminant concentrations, the residents' ventilation practices, indoor air quality perceptions, and decision factors regarding ventilation and indoor air quality-related actions. Measurements of indoor and outdoor air quality and ventilation parameters were made in the summer and fall of 2007 and the winter of 2007–2008. Indoor air concentrations of 22 volatile organic compounds, formaldehyde, acetaldehyde, $PM_{2.5}$ particulate matter, nitrogen dioxide, carbon monoxide, carbon dioxide, temperature, and relative humidity were measured over one 24-hour period. The outdoor air ventilation rates were determined concurrent with the air contaminant measurements using tracer gas measurements. In addition, the field teams measured the building envelope air leakage, garage-to-home air leakage, forced air unit duct leakage, window use, airflow rates, and fan system use. Twenty of the 108 homes were tested in both the summer and winter seasons; four homes were tested in the summer, fall, and winter; and four homes were tested over multiple days, including weekends.

Results and Discussion

The following summarizes the results and provides some of the key discussion points for each of the six study objectives.

Objective 1. Determine how residents use windows, doors, and mechanical ventilation devices such as exhaust fans and central heating and air-conditioning systems.

Occupant Use of Windows and Doors for Ventilation. In this field study, 32 percent of the homes did not use their windows during the 24-hour test day, and 15 percent of the homes did not use their windows during the entire preceding week (Table E1). Most of the homes with no window use were homes in the winter field session. The study concluded that a substantial percentage of homeowners never open their windows, especially in the winter, and confirms the seasonal results from the University of California at Berkeley mail survey and the previous California Air Resources Board-funded statewide survey of human activity patterns. Results from the mail survey indicate that many homeowners never open their windows or doors for ventilation as a result of their concerns for security/safety, noise, dust, and odors.

Table E1. Summary of window and door opening usage during the 24-hour Test Day and the preceding one week.

	Number of Homes Tested	Number of Homes with No Window/Door Usage	Percentage of Homes with No Window/Door Usage (%)
Test Day [a]	108	34	32
Preceding Week [b]	108	16	15

a) Test day usage was measured during the 24-hour air testing day.
b) Preceding week usage was measured during the one week preceding the 24-hour air testing day.

*Occupant Use of Mechanical Outdoor Air Systems***.** For the two types of mechanical outdoor air systems encountered in the field study—ducted outdoor air systems and heat recovery ventilator systems—the median test day use was 2.5 hours for the ducted outdoor air systems (n=14) and 24 hours for heat recovery ventilator systems (n=8). These data indicate that the ducted outdoor air systems, which typically are operated intermittently and in conjunction with the forced air unit fan, operate for only a small portion of the day, while the heat recovery ventilator systems are typically operated continuously. To ensure adequate delivery of outdoor air to the home, ducted outdoor air systems should have a fan cycler, so that even if the thermostat fan switch does not operate the forced air unit fan, the fan is automatically operated for a minimum time. Few of the homes in this study with operational ducted outdoor air systems (four of the 14 homes) had fan cyclers. Thus, to ensure adequate and energy efficient delivery of outdoor air to the home, ducted outdoor air systems should include a fan cycler with fan cycle times and outdoor airflow rates set to provide sufficient outdoor air ventilation.

*Occupant Use of Mechanical Nighttime Cooling Systems***.** For the two types of nighttime cooling systems found in the field study—whole house fan systems and forced air unit return air damper systems—the median test day use was 0.7 hours for whole house fan systems and 5.3 hours for return air damper systems. Use of these systems was confined primarily to the summer months, so the nighttime cooling systems were operated for relatively few hours each day, with the return air damper systems having longer operating times.

Occupant Use of Forced Air Unit Systems. The median test day use for forced air units was 1.1 hours; 32 percent of the homes had zero forced air unit use during the 24-hour test day, and 11 percent had zero use during the entire preceding week. This low operating time of the forced air unit fan limits the effectiveness of ducted outdoor air systems, which depend on the operation of the forced air unit fan, to deliver the required outdoor air.

Objective 2. Measure and characterize indoor air quality, ventilation, and the potential sources of indoor pollutants.

Forced Air Heating/Cooling System Duct Leakage. A total of 86 percent of the homes had duct leakage exceeding the California Title 24 maximum of 6 percent, demonstrating that new homes in California have relatively leaky ducts.

Home Building Envelope Air Leakage Area. The median ACH_{50} (air changes per hour at 50 pascals) for the homes in this study was 4.8 air changes per hour, which compares to a median of 5.2 air changes per hour for a group of homes built since 1992 and 8.6 air changes per hour for a group of homes built before 1987. New Californian homes are generally being built tighter, but not exceptionally tight, like those found in colder climate regions.

Home-to-Garage Air Leakage. A total of 65 percent of the homes did not meet the American Lung Association guideline for a home-to-garage negative pressure of at least -49 pascals when the home is depressurized to -50 pascals with respect to the outdoors. In the three-home pilot study, tracer gas measurements indicated that between 4 percent and 11 percent of the garage sources entered the home. A substantial amount of air from attached garages, which often contain air contaminant sources such as vehicle fuel, exhaust fumes, gasoline-powered lawn equipment, solvents, oils, paints, and pesticides, can enter the home's indoor air.

Mechanically Supplied Outdoor Airflow Rates. Sixty-four percent of ducted outdoor air systems failed to meet the California Energy Commission's new 2008 Building Energy Efficiency Standards. The very low outdoor air exchange rates for the ducted outdoor air systems resulted from a combination of low outdoor airflow rates and short operating times. Heat recovery ventilator systems performed much better. All of the heat recovery ventilator systems met the new 2008 Building Energy Efficiency Standards. These results show that the heat recovery ventilator systems that we tested are a more effective outdoor air supply strategy than the ducted outdoor air systems.

The performance of the ducted outdoor air systems is poor because these systems (1) lacked controls (such as fan cyclers) to ensure adequate operating times of the forced air unit fan, and (2) lacked proper sizing and balancing of the outdoor air duct to ensure sufficient outdoor airflow rate into the system when the forced air unit fan was operated.

In addition, the performance of intermittent mechanical outdoor air systems (such as ducted outdoor air systems) is not equivalent to continuous systems (such as heat recovery ventilator systems) with respect to controlling the short-term exposures to indoor air contaminants, especially if the cycle times are long (for example, greater than two hours). The 2008 Building Energy Efficiency Standards, which were adopted after this study was completed, require a minimum operation time of 1 hour every 12 hours. During extended outdoor air ventilation off-times, intermittent ventilation systems allow for air contaminants with indoor sources to increase substantially as compared to the increases that would occur with a continuous ventilation system. For some indoor air contaminants, such as those that cause irritation and/or odor, the effects are initiated by the immediate exposure to the indoor concentration rather than prolonged exposure to a concentration over a period of time. For such compounds, intermittent ventilation systems may not be sufficient for reducing indoor concentrations to acceptable levels.

Tracer Gas Measurements of Home Outdoor Air Exchange Rates. The median 24-hour outdoor air exchange rate measurement was 0.26 air changes per hour, with a range of 0.09 air changes per hour to 5.3 air changes per hour (Table E2). A total of 67 percent of the homes had outdoor air exchange rates below the minimum California Building Code requirement of 0.35 air changes per hour.

Table E2. Summary comparison of outdoor air exchange rate measurements and CBC 2001 minimum code requirements.

	Number of Homes Tested	Minimum Air Exchange Rate (ach)	Median Air Exchange Rate (ach)	Maximum Air Exchange Rate (ach)	CBC Code Requirement (ach)*	Percentage of Homes Below CBC Code Requirement (%)
24-Hour Measurement	106	0.09	0.26	5.3	0.35	67

* 2001 California Building Code, Appendix Chapter 12, Interior Environment, Division 1-Ventilation, Table A-12-A, Outdoor Air Requirements for Ventilation, Living Areas. Air changes per hour (California Building Code 2001).

The relatively tight envelope construction, combined with the fact that many people never open their windows for ventilation, resulted in many homes with low outdoor air exchange rates.

Indoor Air Contaminant Concentrations. The only indoor air contaminants that exceeded recommended non-cancer and non-reproductive toxicity guidelines were formaldehyde and $PM_{2.5}$ particulate matter. For formaldehyde, 98 percent of the homes exceeded the 2008 Chronic and 8-hour Reference Exposure Levels for irritant effects of 9 micrograms per cubic meter, 59 percent exceeded the 2005 California Air Resources Board's indoor air guideline for irritant effects of 33 micrograms per cubic meter, and 28 percent exceeded the 2008 Acute Reference Exposure Levels for irritant effects of 55 micrograms per cubic meter (Table E3). None of the homes exceeded the 2008 Reference Exposure Levels for acetaldehyde. For $PM_{2.5}$, only one home, with an indoor concentration of 36 micrograms per cubic meter, exceeded the U.S. Environmental Protection Agency's $PM_{2.5}$ 24-hour ambient air quality standard of 35 micrograms per cubic meter.

Table E3. Summary comparison of indoor concentrations of formaldehyde, acetaldehyde, and indoor air contaminant guidelines.

Compound	Number of Homes Tested	Minimum Concentration ($\mu g/m^3$)	Median Concentration ($\mu g/m^3$)	Maximum Concentration ($\mu g/m^3$)	Indoor Air Guideline ($\mu g/m^3$)	Percentage Above Indoor Air Guideline (%)
Formaldehyde	105	4.8	36	136	2 [a]	100
					9 [b]	98
					9 [c]	98
					33 [d]	59
					55 [e]	28
Acetaldehyde	105	1.9	20	102	4.5 [a]	93
					140 [b]	0
					300 [c]	0
					470 [e]	0

a) Proposition 65 No Significant Risk Level for carcinogens (OEHHA 2008a).
b) Office of Environmental Health Hazard Assessment Chronic Reference Exposure Levels, 2008 (OEHHA 2008b). Adopted after study completed.
c) OEHHA 8-hour Reference Exposure Levels, 2008 (OEHHA 2008b). Adopted after study completed.
d) *Indoor Air Quality Pollution in California* (California Air Resources Board 2005).
e) OEHHA Acute Reference Exposure Levels, 2008 (OEHHA 2008b). Adopted after study completed.

Most new homes had indoor formaldehyde concentrations that exceeded recommended guidelines.

Volatile Organic Compound Proposition 65 Safe Harbor Levels. For each of the seven volatile organic compounds with No Significant Risk Levels for cancer, there were some homes that exceeded the No Significant Risk Levels concentration indoors. As summarized in Table E3 for formaldehyde and acetaldehyde, the percentages of homes exceeding the No Significant Risk Levels concentration were 100 percent and 93 percent, respectively. For the five other volatile organic compounds, the percentage of homes exceeding the No Significant Risk Levels concentration ranged from 8 percent for trichloromethane (chloroform) and tetrachloroethene to 63 percent for benzene.

For the two volatile organic compounds with Maximum Allowable Dose Levels for reproductive toxicity, only the benzene Maximum Allowable Dose Levels was exceeded. A total of 20 percent of the homes had indoor benzene concentrations that exceeded the calculated indoor Maximum Allowable Dose Levels concentration. Thus, a substantial percentage of new homes have indoor concentrations that exceed recommended guidelines for cancer and/or reproductive toxicity.

Potential Sources of Indoor Air Contaminants. The primary source of the indoor concentrations of formaldehyde and acetaldehyde, which were the two air contaminants that most frequently exceeded recommended guidelines, is believed to be composite wood products. While the research team was not able to determine the extent to which formaldehyde-based resins were used in the composite wood identified in the homes, formaldehyde-based resins are the most common resins used in the production of composite wood products. The composite wood identified in these homes include particleboard that was used in 99 percent of the kitchen and bathroom cabinetry, as well as many pieces of furniture. Other sources of composite wood include plywood and oriented strand board in walls, subfloors, and attics, and medium density fiberboard in baseboards, window shades, interior doors, and window/door trims.

Potential sources of some volatile organic compounds were identified for homes with elevated indoor volatile organic compound concentrations. The following potential sources of indoor air contaminants are suggested from a comparison of the occupant activity logs and house characteristics with the indoor contaminant concentrations and emission rates: 1,4-dichlorobenzene and naphthalene from mothballs, d-limonene from furniture polish and cleaning chemicals, 2-butoxyethanol from anti-bacterial wipes, toluene from air fresheners, and tetrachloroethene from dry cleaned clothes or drapes.

Objective 3. Determine occupant perceptions of, and satisfaction with, the indoor air quality in their homes.

A total of 28 percent of the households reported experiencing one or more of nine physical symptoms during the previous three weeks that they did not experience when they were away from the home. The three most frequently reported symptoms were nose/sinus congestion (19 percent), allergy symptoms (15 percent), and headache (13 percent). The three most frequently reported thermal comfort perceptions were "too cold" (19 percent), "too hot" (15 percent), and "too stagnant (not enough air movement)" (12 percent). Thus, a substantial percentage of occupants of new homes report experiencing physical symptoms or thermal discomfort.

Objective 4. Examine the relationships among home ventilation characteristics, measured and perceived indoor air quality, and house and household characteristics.

Statistical comparisons were conducted for indoor formaldehyde and acetaldehyde concentrations, outdoor air exchange rates, and window usage. Formaldehyde and acetaldehyde were selected for these analyses, as these were the two air contaminants that most frequently exceeded recommended indoor concentration guidelines. Because of the small number of homes in the sample groups and the important seasonal and house-specific differences, these comparisons should only be considered as suggestive of differences. Multivariate analyses need to be done to further establish any differences between the groups.

Formaldehyde concentrations were found to be significantly higher in the following group comparisons:

- Non-mechanically ventilated Northern California homes had higher formaldehyde concentrations than Southern California homes
- Ducted outdoor air homes had higher formaldehyde concentrations than homes without mechanical outdoor air ventilation systems
- Ducted outdoor air homes had higher formaldehyde concentrations than heat recovery ventilator homes

Acetaldehyde concentrations were found to be significantly higher in the following group comparisons:

- Ducted outdoor air homes had higher acetaldehyde concentrations than homes without mechanical outdoor air ventilation systems
- Ducted outdoor air homes had higher acetaldehyde concentrations than heat recovery ventilator homes

Window usage was found to be significantly higher in the following group comparisons:

- Summer homes had higher window usage than winter homes

Outdoor air exchange rates were found to be significantly higher in the following group comparisons:

- Heat recovery ventilator homes had higher outdoor air exchange rates than homes without mechanical outdoor air ventilation systems
- Heat recovery ventilator homes had higher outdoor air exchange rates than ducted outdoor air homes

Correlation analyses were also conducted for indoor formaldehyde and acetaldehyde concentrations with six home characteristics and four environmental conditions. For both formaldehyde and acetaldehyde concentrations, the outdoor air exchange rate was determined to have a significant inverse correlation. For formaldehyde concentrations, indoor air temperature was determined to have a significant correlation. These results indicate that as outdoor air exchange rates decrease or the indoor temperate increases, the indoor concentrations of formaldehyde increase.

Objective 5. Identify the incentives and barriers that influence people's use of windows, doors, and mechanical ventilation devices for adequate air exchange.

Of the homeowners with mechanical outdoor air systems (that is, ducted outdoor air or heat recovery ventilator systems, not nighttime cooling systems, evaporative cooling systems, or window fans):

- 78 percent stated that the operation of the system was explained to them when they bought or moved into the house
- 63 percent responded that they understood how the system works
- 83 percent stated that they felt that they understood how to operate the system properly

A total of 91 percent stated they chose the system because it came with the house, and the things they liked most about the system were: "Fresh air" (52 percent), "Quiet" (48 percent), and "Reduced concern about indoor air quality" (26 percent). The things they liked least about the system were: "Not effective" (32 percent), "Too drafty" (26 percent), and "Too noisy" (26 percent).

Objective 6. Identify the incentives and barriers related to people's purchases and practices that improve indoor air quality, such as the use of low-emitting building materials and improved air filters.

A total of 24 percent of the 105 respondents stated "none" in response to the question "What special measures or choices have you or the builder taken to improve the quality of the air in your home?" The four most frequent responses to improvements undertaken were: "Hard flooring instead of carpeting" (33 percent), "Carbon monoxide alarm" (28 percent), "High efficiency vacuum cleaner with special features such as filters to trap more particles" (27 percent), and "Upgrade my central air filter" (25 percent).

Conclusions

The following summarizes the main conclusions from this study of new single-family homes built in California in 2002–2004.

1. Many homeowners never open their windows or doors, especially in the winter months.
2. New homes in California are built relatively tight, such that outdoor air exchange rates through the building envelope can be very low (e.g., 0.1 air changes per hour).

3. In new homes with low outdoor air exchange rates, indoor concentrations of air contaminants with indoor sources, such as formaldehyde and some other volatile organic compounds, can become substantially elevated and exceed recommended exposure guidelines.

4. Ducted outdoor air mechanical outdoor air ventilation systems generally did not perform well as a result of the low outdoor airflow rates and short operating times. A total of 64 percent of ducted outdoor air systems failed to meet the American Society of Heating, Refrigerating and Air-Conditioning Engineers 62.2-2007 standard for residential ventilation, which is referenced in the Energy Commission's 2008 Building Energy Efficiency Standards.

5. Heat recovery ventilator mechanical outdoor air ventilation systems performed much better than ducted outdoor air systems. All heat recovery ventilator systems met the California Energy California's new 2008 Building Energy Efficiency Standards.

Recommendations

1. Consideration should be given to installing mechanical outdoor air ventilation systems in new single-family residences to provide a dependable and continuous supply of outdoor air to the residence for the purpose of controlling indoor air contaminants.

2. Consideration should be given to regulating the emissions of air contaminants from building materials, such as the 2007 California Air Resources Board regulation to limit formaldehyde emissions from composite wood products.

3. Given the relatively high frequency of indoor formaldehyde concentrations that exceeded recommended exposure guidelines, and the fact that formaldehyde is a known human carcinogen, consideration should be given to conducting studies focused on quantifying the emission rates of formaldehyde from all potential indoor sources (such as building materials, furnishings, consumer products, and others). Based on this research, regulations should be developed to reduce indoor formaldehyde emissions.

4. Outreach to public and professional groups should be increased regarding the need to reduce indoor formaldehyde concentrations in existing homes by sealing exposed composite wood surfaces, selecting low-emission furniture, improving outdoor air ventilation in the home, and controlling indoor humidity.

5. Multivariate analyses of the data collected in this study should be conducted to further develop the understanding of the relationships between indoor air

contaminant concentrations, indoor sources, ventilation, season, and other major sources of variance.

6. A statewide population-weighted assessment from the data collected in this field study should be performed to better understand the air contaminant source and ventilation characteristics of new homes.

7. Additional studies of indoor air quality and ventilation with diurnal wind speed and temperature swings should be conducted to examine the significance of nighttime cooling by natural or mechanical means.

8. Further studies in additional homes with mechanical outdoor air ventilation systems should be conducted to confirm the findings identified in this study and with consideration for other building factors. Both installation and field performance of the mechanical outdoor air ventilation systems should be evaluated.

9. Revision of the intermittent ventilation effectiveness factors in the 2008 Building Energy Efficiency Standards and the Energy Commission's companion Residential Compliance Manual should be considered, to provide intermittent ventilation that results in indoor air quality that is comparable to that provided by continuous ventilation systems.

10. Research should be conducted on exhaust-only ventilation systems, which were not encountered in this study but may be used widely in the future.

11. Home builders should be educated about the importance of conveying to homeowners the need for outdoor air ventilation in homes, how the ventilation systems operate, and the importance of designing systems that are easy for homeowners to maintain. In addition, consider creating an easy-to-read short fact sheet that can be distributed to the public regarding residential ventilation systems and the importance of the operation and maintenance of these systems to indoor air quality.

12. Research should be conducted to investigate residential exposures to ozone-initiated reaction products, such as formaldehyde and other aldehydes and ultrafine particles, that are formed when ozone reacts with contaminants such as d-limonene, which is emitted by many air freshener and cleaning products as well as some orange oil termite treatments. This project's database contains important information for such research, including d-limonene concentrations, outdoor air exchange rates, air cleaners that generate ozone, and formaldehyde and other aldehyde concentrations.

Benefits to California

This was the first large field study of window use, outdoor air ventilation rates, and indoor air contaminants in new California homes. The data from this study were immediately useful for the California Energy Commission in guiding the development of building design standards that require mechanical ventilation to protect indoor air quality and comfort in California homes and for the California Air Resources Board to improve exposure assessments of indoor and outdoor air contaminants. In particular, the Energy Commission used the study results as a scientific basis to revise the State's building energy efficiency standards to provide more healthful, energy-efficient homes in California. The study results will also improve California Air Resources Board's ability to identify current sources of indoor air contaminants, to assess Californians' current exposure to measured toxic air contaminants, and to recommend effective strategies for reducing indoor air pollution.

1.0 Introduction

Concerns have been raised about whether homeowners use windows, doors, exhaust fans, and other mechanical ventilation devices enough to remove indoor air contaminants and excess moisture. Building practices and building standards for energy efficiency have led to more tightly sealed homes, and building codes have relied on occupants to open windows for ventilation. However, there is very little information on current ventilation practices, indoor air quality (IAQ), or indoor air contaminant sources in homes.

In 2005, the California Air Resources Board (ARB) prepared a comprehensive report on indoor air quality in response to requirements of Assembly Bill 1173, *Report to the California Legislature–Indoor Air Pollution in California* (California Air Resources Board 2005). This report summarizes the best scientific information on indoor air pollution, including: information on common indoor air contaminants and their sources; the potential health impacts of indoor air contaminants and associated costs; existing regulations and practices; and options for mitigation in schools, homes, and non-industrial workplaces. This report concludes that indoor air pollution causes substantial, avoidable illness and health impacts–ranging from irritant effects to asthma, cancer, and premature death–and costs Californians billions of dollars each year.

Phillips et al. (1990) reported results of a statewide telephone survey of 1,780 Californians conducted in 1987–1988 regarding the occupant's use of mechanical and natural ventilation. The authors reported that a sizable number of households only open windows/doors for natural ventilation for a few minutes a day at most, especially during the winter (25% never open windows/doors for ventilation). In addition, very few households use exhaust fans. Based upon the results of this survey the authors conclude that in homes where the occupants do not use windows/doors or mechanical systems for ventilation, that these households may be susceptible to high concentrations of indoor air contaminants.

In addition to the fact that many homeowners do not use windows/doors for ventilation, the building envelope tightness in new Californian homes has been increasing, which reduces the natural infiltration of outdoor air into residences. Wilson and Bell (2003), report that construction practices have resulted in lower infiltration rates. The building envelope air tightness as determined from blower door tests in a sample of 76 homes built in California since November 2002 had a median ACH_{50} (i.e., air changes per hour at 50 pascals [Pa]) of 5.2, with a range of 2.3 to 8.7; while in a sample of 13 homes built before 1987, the median ACH_{50} was 8.6, with a range of 6.2 to 13.2. In addition, Chan et al. (2003) report in an analyses of more than 70,000 measurements in the U.S. housing stock that envelope leakage has been steadily decreasing. For conventional homes that are not participants of a low-income or an energy-efficiency program and that have floor areas between 1500 square feet (ft^2) to 2000 ft^2, the median normalized envelope leakage area has decreased from 0.67 in homes built before 1950, to 0.49 for homes built between 1950 and

1979, to 0.38 for homes built between 1980–1995, to 0.31 for homes built between 1995 and 2002.

In recognition that many homeowners often do not use windows for outdoor air ventilation and that residential building envelopes have evolved to be more airtight, the State of Washington has, since 1991, required mechanical outdoor ventilation for residences. A 1999 field study (Devine 1999) of 31 homes built since 1991 with mechanical outdoor ventilation systems revealed that the technical details of the mechanical outdoor air ventilation requirements were widely misunderstood. While all 31 homes evaluated were equipped with at least some system components, less than half (15) met the requirements either prescriptively or by performance.

Batterman et al. (2005) reported that attached garages may be important sources of air contaminants in the home. In a study of 15 residential garages, the authors observed elevated concentrations of volatile organic compounds in the garage air. The calculated emission rates of 34 volatile organic compounds in the 15 garages, totaled 3.0 ± 4.1 grams (g)/day and were dominated be gasoline-related compounds (e.g., benzene, toluene, and xylenes). Although the impact of the concentrations of volatile organic compounds (VOC) in the garage air upon the indoor air concentrations of the residences was not assessed in this study, the authors conclude that garages are potentially significant sources of VOC into the air of residences.

Hodgson and Levin (2003) reported the indoor concentrations of VOC in two studies involving 20 new single-family homes. The VOC concentrations with maximum concentrations of 50 parts per billion (ppb) or more included formaldehyde, acetaldehyde, hexanal, toluene, ethylene glycol, 1,2-propanediol, 2-propanaone, and alpha-pinene.

Hodgson et al. (2000) reported in a study of new manufactured and site-built homes that formaldehyde is by far the most likely of the 12 VOCs evaluated to produce sensory irritation effects. Phenol and acetic acid were also identified as relatively potent irritants. Multiplying the relative irritancy for these three VOCs by the geometric mean indoor concentration measured in the seven site-built homes in this study results in acetic acid contributing 17 times more times sensory irritation than phenol, and formaldehyde contributing 419 time more. In addition to the sensory irritant effects of formaldehyde, in 2004, the World Health Organization designated formaldehyde as a known human carcinogen (IARC 2004).

Hodgson et al. (2002) measured the emission rates of formaldehyde in a new, fully furnished but unoccupied manufactured home. The materials with the highest percentage of the total emission rates of formaldehyde were determined to be to the particleboard cabinetry cases (36%) and the high density fiberboard passage doors (32%).

To help better understand ventilation and the impact upon air quality in new Californian homes, a mail survey of new single-family detached homes was conducted to determine occupant use of windows, barriers that inhibit their use, satisfaction with IAQ, and the relationships between these factors (Price et al. 2007). This study, sponsored by the ARB and the California Energy Commission (Energy Commission), was conducted by the University of California, Berkeley (UCB) Survey Research Center. In December 2004 and January 2005 a questionnaire was mailed to a stratified random sample of 4,972 single-family detached homes built in 2003. A total of 1,448 responses were received. An additional sample of 230 homes was obtained from builders. These additional homes were also mailed the questionnaire and were reported by the builders to have mechanical ventilation systems. A total of 67 responses were received from this sample.

Table 1 (page 17) summarizes the percentage of homes responding to the questionnaire that reported no use of windows for ventilation on a seasonal basis. The results are presented for four categories of never-used hours per day: 24-hours/day (i.e., never opened), 23 or more hours/day, 22 or more hours/day, and 21 or more hours/day; corresponding to 0 hours, 1 or less hours, 2 or less hours, and 3 or less hours of window usage per day. As can be seen in Table 1, a substantial percentage of homeowners, ranging from 5.8% in the spring to 29% in the winter, report never using their windows. The percentage of homeowners reporting 21 or more hours per day of no window usage ranged from 12% in the spring to 47% in the winter.

The reasons reported most frequently as "very important" by the homeowners (i.e., 20% or more of homeowners) for not opening their windows included: security/safety (80%), maintain comfortable temperature (68%), keep out rain/snow (68%), save energy (61%), keep out insects (52%), keep out dust (42%), too windy/drafty (45%), keep out noise (39%), reduce air contaminants or odors from outdoors (36%), keep out pollen/allergens (35%), privacy from neighbors (29%), and keep out woodsmoke (23%).

In July 2005 as a follow-up to the UCB mail survey, a large indoor air quality field study entitled *Ventilation and Indoor Air Quality in New Homes*, sponsored by the California Air Resources Board and the California Energy Commission, was launched to assist in answering some of the questions regarding ventilation and indoor air quality in new single-family detached homes.

This field study involved 108 new single-family homes from Northern and Southern California, including a subset of 26 homes with mechanical outdoor-air ventilation systems. The field teams measured home ventilation and indoor contaminant source characteristics, including the amount of composite wood associated with cabinetry/furnishings and the finishes of floors, walls, and ceilings; indoor contaminant concentrations; the residents' ventilation practices; IAQ perceptions; and decision factors regarding ventilation and IAQ-related actions. Measurements of indoor and outdoor air quality and ventilation parameters were made in the summer, fall, and winter. Indoor air concentrations of volatile organic compounds; aldehydes (including formaldehyde); $PM_{2.5}$ particulate matter; nitrogen dioxide; carbon monoxide; carbon dioxide; temperature; and relative humidity were measured over one 24-hour period. The outdoor air ventilation rates were determined concurrent with the air contaminant measurements using passive perfluorocarbon tracer (PFT) gas measurements. In addition, the field teams measured the building envelope air leakage, garage-to-home air leakage, forced air unit duct leakage, window use, airflow rates, and fan system usage. Twenty of the 108 homes were tested in both the summer and winter seasons, and four homes were tested in the summer, fall, and winter. Four homes were tested over multiple days, including weekends.

This study provides, for the first time, statewide, accurate and current information on both ventilation and IAQ in new California homes. Indoor air quality and household ventilation practices were obtained from multiple seasons and regions of the state, which will help characterize the full range of indoor air contaminant exposure in such homes. Measured levels of ventilation and IAQ were compared to current guidelines and standards. Information on the use of windows, fans, and central systems will help establish realistic values for developing California building energy efficiency standards.

The Energy Commission used the study results as a scientific basis to revise the state's building energy efficiency standards, in order to provide more healthful, energy-efficient homes in California. The study results will improve ARB's ability to identify current sources of indoor air contaminants, to assess Californians current exposure to measured toxic air contaminants, and to recommend effective strategies for reducing indoor air pollution.

1.1 Project Study Objectives

This project has the following six specific study objectives:

1. Determine how residents use windows, doors, and mechanical ventilation devices such as exhaust fans and central heating and air-conditioning systems.

2. Measure and characterize IAQ, ventilation, and the potential sources of indoor pollutants.

3. Determine occupant perceptions of, and satisfaction with, the IAQ in their homes.

4. Examine the relationships among home ventilation characteristics, measured and perceived IAQ, and house and household characteristics.

5. Identify the incentives and barriers that influence people's use of windows, doors, and mechanical ventilation devices for adequate air exchange.

6. Identify the incentives and barriers related to people's purchases and practices that improve IAQ, such as the use of low-emitting building materials and improved air filters.

1.2 Report Organization

Section 2, Project Approach / Materials and Methods, describes the study design, participant recruitment, and measurements methods for home characteristics, window and mechanical ventilation system usage, outdoor air exchange rates, indoor air contaminants, and occupant perceptions and decision factors.

Section 3, Project Outcomes / Results and Discussion, presents and discusses the results associated with each of the study objectives.

Section 4, Conclusions and Recommendations, presents the research team's conclusions and recommendations.

Because there are so many large tables and figures in this report, in order to not have frequent and multiple page interruptions of the report text, the figures and tables have been placed at the end of each section in which they are introduced. To help readers locate the specific table or figure, the page number is included in the text of the report.

Table 1. Seasonal percentage of new California single-family detached homes reporting no use of windows for 24, 23, 22, and 21 hours per day.

Percentage of Homes Surveyed Reporting No Use of Windows [a] for the Indicated Number of Hours per Day (N = 1,334)				
	24 hours/day	23 or more hours/day	22 or more hours/day	21 or more hours/day
Summer	7.5	9.1	12	14
Fall	8.6	12	16	18
Winter	29	36	45	47
Spring	5.8	5.8	8.4	12

a) *Study of Ventilation Practices and Housing Characteristics in New California Homes* (Price et al. 2007).

2.0 Project Approach/Material and Methods

2.1 Study Design

This study's design involved recruitment of 108 new Californian homes utilizing the UCB mail survey database, although it was anticipated that some additional homes outside of the UCB mail survey database would need to be recruited to fulfill the requirements of the proposed study sample. Only single-family detached homes built after January 2002 that were owner-occupied primary residences for at least one year were eligible for the field study. Additionally, if occupants reported tobacco smoking inside the homes, they were excluded from the field study. The intent was to have homes that were recently built under the latest California building standards (i.e., 2001), including the California Building Code (California Building Standards Commission 2001) and the California Title 24 Energy Efficiency Standards (California Energy Commission 2001a and 2001b). The intent was also to include occupants who would recollect their "new-home experience" but had been in the home long enough to be familiar with its operation across the year (four seasons).

Our proposed home sample frame consisted of a total of 108 California new single-family detached homes, with a total of 54 homes from the South Coast (Los Angeles and San Diego) region and 54 homes in the Central Valley / Delta (Sacramento) region. Our sample frame also required for the 54 homes in each region to be divided into 27 homes for testing in the winter field session and 27 homes for testing in the summer field session. In addition, our sample frame required inclusion of a minimum of 20 mechanically ventilated homes (i.e., homes with mechanically supplied outdoor air to the whole house) selected to represent at least three major manufacturers of these type systems.

Additionally, our study plan required the following crossover/repeat testing of homes:

- 10 of the 54 homes in each region were selected for retesting during the alternate season (summer or winter).

- The 4 homes of the 5 seasonal repeat homes in Northern California were retested during the fall swing season.

- 2 of the 27 winter and 2 of the 27 summer homes in Northern California were selected for testing on 2 additional consecutive 24-hour periods, which include one additional week day and one weekend day (i.e., Thursday, Friday, and Saturday).

Our study plan also required, to the extent there was sufficient sample in excess of those required to fulfill the primary selection criteria, to select homes following secondary selection criteria, which were requested by the ARB and Energy Commission. These criteria were:

- Match the 60/20/20 percentage mix from the UCB mail survey three strata: Rest-of-State, Sacramento Delta, and Southern California Coastal

- Northern California Inland

    - Use the Rest of the State stratum to identify the homes in the Central Valley from Merced north

    - Exclude homes in the Sacramento Delta Stratum

    - Exclude San Jose homes

- Northern California Delta

    - Include the homes in the Sacramento Delta Stratum

    - Exclude homes in the Bay Area

- Southern California Inland

    - Use the Rest of the State Stratum to identify homes in the areas from about Lancaster south

    - Exclude the Southern California Coastal Stratum homes

- Southern California Coastal

    - If there are few homes available in this group, include some homes in the high desert areas of Lancaster, Palmdale, areas east to Victorville, or in the Lake Elsinore area. Verify that these areas meet the Energy Commission screening criteria for nighttime ventilative cooling potential: Summer maximum temperature of at least 90°F and nighttime minimum temperature at least 30°F lower.

    - Exclude homes if less than two miles from the coast.

2.2 Home Recruitment and Selection

To recruit the homes for this study, the database from the UCB (Price et al. 2007) mail survey that was administered in 2004–2005 was utilized, along with supplemental listings of new homes (i.e., built since 2002) in the same areas as homes already identified. The UCB mail survey drew a random sample of 10,000 new single-family homes from a listing by DataQuick, which had the best available records of this type. This list was stratified: 2,000 homes from the Sacramento Delta area, 2,000 from the Southern Coastal area, and 6,000 from the rest of the state. The first two strata were defined by zip code areas where substantial nighttime cooling was expected in the summer due to coastal or delta wind influence. About one-half of the selected homes in each stratum were sent a recruitment letter. Over 300 of those homes were ineligible, mostly because the residents had not lived in the home at least nine months, the home was vacant, or the address was incorrect.

In this stratified-random sample by UCB survey, known as the Statewide Probability Sample, a total of 4,648 eligible homes were contacted, and 1,448 of those homes completed the mail questionnaire, for a 31% response rate. The participating homes from this sample have a sample weight assigned to them to adjust for the different sampling rates and the slightly different response rates for each stratum.

The UCB Statewide Probability Sample appears to be fairly representative of new single-family homes in California. The survey response rate of 31% was very good for mail surveys, which usually achieve a response rate of about 10%. As discussed by Price et al. (2007), the ethnic composition of the households was similar to the California population as a whole, except that the fraction of Asian households was a little larger than that for California. As expected for recent homebuyers, the households had higher incomes and household sizes compared to the general population.

In addition to recruiting the Statewide Probability Sample, the UCB mail survey recruited a Supplementary Builders' Sample of new homes reported by the builders to have outdoor air mechanical ventilation systems. This sample listing consisted of homes built by a Northern California building firm with homes mainly in the Sacramento Delta area, homes built in Southern California as part of the U.S. Department of Energy (2007) Building America program and homes identified by ARB staff. Out of 192 eligible homes from this group, 67 completed the questionnaire, for a response rate of 35%.

For the present study, the research team tried to contact participants in the UCB mail survey who had previously indicated their willingness to participate in a field study involving measurements of ventilation and indoor air quality in their homes. Out of all the completed questionnaires in the UCB survey (1,515), 965 respondents (66%) of the respondents indicated such willingness. About one-third (340) of these respondents were located in Northern California, and two-thirds (624) were located in Southern California. A total of 126 respondents (107 in Northern California and 19 in Southern California) were excluded from the study due to their location in areas with coastal influences (Bay Area in Northern California; proximity to the coast in Southern California.).

Unfortunately the database did not contain telephone numbers for the 965 respondents; a search by address returned phone numbers for 300 (32%) of them.

Initial recruiting attempts failed to obtain the target sample sizes because of the limited number of potential participants and the need to cluster homes geographically. Therefore, in addition to the interested respondents to the UCB mail survey, supplemental DataQuick listings of owners of new (2002 to 2004 vintage) single-family detached homes from the neighboring areas were purchased. This supplemental listing had 8,345 addresses, homeowner names, and telephone numbers.

From this overall sample listing consisting of UCB sample homes and the supplemental DataQuick sample, recruitment letters were mailed. A copy of the recruitment letter and recruitment script is in the appendices of the Pilot Report, in Appendix A of this report. The letters asked for homeowners interested in participating in the field study to call the project participant recruiters' toll-free number. The letters also offered a $100 incentive in addition to providing the indoor air quality and ventilation system testing to those who participated in the field study. Calls were received from interested homeowners and the calls were placed to those non-responding homeowners for which telephone numbers were available.

Upon making contact with the interested homeowners the research team administered a recruitment script and collected information on the home, occupancy, and ventilation systems and described the details of the three visits required by the field teams. Researchers also collected information regarding the participants' preferences for dates and times of the three field visits with the understanding that the same time periods would be required for each of the three field visits. These were:

- Time Period 1: 9 AM to 12 PM
- Time Period 2: 1 PM to 4 PM
- Time Period 3: 4 PM to 7 PM

The recruiters informed the homeowners that those who indicated flexibility in the field visit dates and times would have a much higher probability of being selected.

Upon completion of the administration of these recruiting scripts to interested homeowners, the homes for the field study were selected based on the primary and secondary sampling criteria discussed above.

2.3 Field Work Teams and Work Assignments

The fieldwork was divided amongst three field teams, each consisting of two field technicians. All fieldwork was conducted according to the specific standard operating procedures (SOPs) developed for each of the three field teams.

Field Team 1 installed PFT sources, installed data loggers on windows and fans, and administered the Occupant Fan and Window Logs, the Indoor Contaminant Source Activity Sheet, and the Occupant Questionnaire one week in advance of the field work performed by Field Teams 2 and 3.

Field Team 2 followed Field Team 1 by 7–10 days, to allow for the PFT sources to equilibrate. Their duties included: the installation and start of the air contaminant sampling equipment at an indoor and outdoor location, installation and start of the PFT samplers, collecting information on home construction characteristics, and collecting an inventory of indoor air contaminant sources.

Field Team 3 followed Field Team 2 by 22–26 hours. This field team was responsible for the removal of the air sampling equipment, the PFT samplers, window/door and fan logs and loggers, collecting detailed information on building air leakage, duct air leakage, and ventilation system airflow rates.

2.4 Home and Site Characteristics Collection

Characteristics of each home were collected using forms that were filled out by the field team members during the home inspections. The forms used to record these data are the Home Characteristics Form 1, PFT Form, Home Floor Plan Sketch or floor plan provided by the homeowner, Home Characteristics Form 2, and Room Tally Form. The following list describes the home characteristics that were collected in each home:

- General Characteristics
    - number of occupants
    - number of stories
    - foundation type
    - conditioned floor area, volume and envelope area
    - area of openable windows and doors

- Mechanical Characteristics
    - heating/cooling system: general description, location, filter type, duct locations, airflow rates
    - mechanically supplied outdoor air system: general description and airflow rates
    - exhaust fans: number, controls, and airflow rates

- appliances: fuel type, venting, location
- other ventilation/conditioning equipment: general description and airflow rates
- air cleaning devices: type, manufacturer, and model

- Site Characteristics
  - outdoor air contaminant sources (e.g., busy roadways, nearby gasoline stations)
  - site drainage conditions
  - site wind shielding

- Home Contaminant Source Characteristics
  - vacuum system - type and typical usage frequency
  - number of occupants and pets
  - mechanical system fuels
  - composite wood materials
  - type of floor surface
  - moisture staining/damage

The conditioned floor area, envelope area, and air volume was calculated from on site dimension measurements. Floor plans were obtained for each of the homes. Field Team 1 collected on-site measurements of the home exterior dimensions, indoor ceiling heights, and selected indoor wall dimensions. These dimensions were then used to calculate a scale factor for the floor plans, and this scale factor was used to calculate the conditioned floor areas, envelope areas, and air volumes on a room-by-room basis for the entire home.

The amount of composite wood in each home was calculated as the combined sum of the square feet associated with furniture/cabinetry and the finishes of floors, walls, and ceilings. There were a substantial amount of composite wood products that were likely present but could not be verified without damaging the surfaces. These included medium-density fiberboard baseboards, interior doors, window trim, window shades, and plywood subflooring. In addition, data were not collected on whether the composite wood product was covered with a laminate.

2.5 Home Air Leakage Measurements

2.5.1 Forced Air Unit Heating/Cooling System Duct Leakage

Testing for forced air unit (FAU) duct leakage was conducted in accordance with ASTM E1554-03, Standard Test Method for Determining External Air Leakage of Air Distribution Systems by Fan Pressurization (ASTM 2003a). The method uses a fan flow meter device (i.e., DuctBlaster) attached to the return air grill, which measures the airflow required to pressurize the ducts to 25 Pa while the supply ducts are sealed. The FAU system duct leakage airflow was then divided by the total FAU return airflow to get the percent duct leakage.

2.5.2 Building Envelope Air Leakage Area

The building envelope air leakage area was determined by Field Team 3, using a depressurization multipoint blower door test with automated pressure testing (APT) instrumentation. Testing was conducted in accordance with ASTM E779-99, Standard Test Method for Determining Air Leakage by Fan Pressurization (ASTM 2003b). For this test the homes were configured with all windows and exterior door closed, all interior doors open (except doors to attached garages and hatches to attics), fireplace dampers closed, and all exhaust fans off. The continuously operating mechanical outdoor air delivery fans (i.e., the heat recovery ventilator systems [HRVs]) were left operating. Windy outdoor conditions during testing of a few homes were such that a multipoint blower door test was not possible. For these homes a single point depressurization blower door test was conducted at 50 pascals of pressure.

2.5.3 Home-to-Garage Air Leakage

Home-to-garage air leakage measurements were collected by Field Team 3 using two methods to measure the potential air leakage between the home and the garage. The first method consisted of using a blower door with APT instrumentation to conduct a zone pressure diagnostic test of the garage-to-home connection. This test consists of conducting two multi-point blower door home depressurization tests as described above; one with the home door to the garage closed and one with the door open. From these data the equivalent leakage area (EqLA @10 Pa) in square inches was calculated between the garage and the home and between the garage and outdoors. The second test method consisted of measuring the differential pressure between the home and the garage while the home was -50 Pa with respect to outdoors. This test is recommended by the American Lung Association in their Health Home Builder Guidelines (American Lung Association 2006). When the home is depressurized to -50 Pa with respect to outdoors, the home-to-garage negative pressure must be at least -49 Pa. It should be noted that the team contacted members of the Technical Committee for information to determine the basis for this guideline, and there are apparently no specific studies upon which it is based. Thus, it is assumed that this guideline most likely represents the professional judgment of the

Technical Committee with respect to a garage-home coupling factor that is both relatively low and achievable.

2.6 Window/Door and Mechanical Systems Usage

The approach for measuring window/door and mechanical system usage applies a combination of one-time tests and weekly monitoring. Collection methods are summarized in this section for the following ventilation parameters:

- windows and doors
- mechanical exhaust fans and appliances
- forced air heating/cooling systems

The usage of select windows and doors, and operation of mechanical systems was monitored for approximately one week by written logs and/or data logger instruments. The amount of time that windows and doors were used and mechanical systems were operated is reported in 24-hour time periods counting back from the time that Field Team 3 entered the home and stopped the IAQ contaminant and PFT measurements.

The following is a description of the methods that were used to collect data on each of the ventilation parameters.

2.6.1 Occupant Use of Windows and Doors

The homeowners were asked by Team 1 which windows and doors, if any, they use for ventilation. Written logs and a writing utensil were placed on the glass or panel, near where the window or door was opened. The homeowners used these logs to record the time, duration, and distance of the window or door opening. The windows or doors that were verified as never being used were not equipped with window written logs. Homeowners were also asked to identify the two windows or doors that were most frequently used for ventilation. Magnetic state loggers were taped to these two windows or doors to record the time and duration that the window or door was opened.

Measurements of all window and door maximum opening areas in the home were collected by Team 1. The opening width and height were measured using a tape measure.

2.6.2 Occupant Use of Mechanical Exhaust Systems

Homeowners were asked by Team 1 which exhaust fans they use for ventilation. Data loggers or written logs were deployed for all exhaust fans that would be used and all exhausting appliances (i.e., dryers).

For bathroom or laundry room exhaust fans, ac-field data loggers were placed above the exhaust grille in the vicinity of the fan motor for the two fans that the homeowners identified as used the most**.** For these exhaust fans with data loggers, no written logs were installed. For any additional exhaust fans, beyond the two equipped with data loggers, written logs and a writing utensil were placed near the fan switch/timer for the homeowners to log the usage. For bathroom and laundry room exhaust fans that are meant to run on a continuous basis, such as HRVs, the homeowner was questioned by Team 1 about usage and for those HRVs that were reported to operate intermittently, either a written log or an ac-field data logger was installed.

For clothes dryer exhaust appliances, an ac-field data logger was hooked directly onto the power cord of the dryer using a zip-tie, and electrical tape if needed, or an ac-field sensor was clamped to the power cord and plugged directly into the data logger.

For kitchen range hood exhaust fans, written logs and a writing utensil were placed on the wall or microwave near the fan switch for the homeowners to log the usage and fan speed.

All bathroom and laundry room exhaust fan airflow rates were determined using a balometer flow hood. Where the exhaust duct was accessible along the exterior wall of the building, kitchen range hood exhaust fan airflow rates were determined using a balometer flow hood. For those homes where the exhaust duct was not accessible, the average air speed was measured at the hood air filters and the filter dimensions were collected using a tape measure.

Where the exhaust duct was accessible along the exterior wall of the building the dryer exhaust airflow rate was determined using a balometer flow hood. While onsite the number of bends (e.g., 90^0, 45^0) and the length of the ductwork were estimated and the dryer make and model information was collected. For homes where the exhaust duct was not accessible, these characteristics were used to calculate the estimated dryer exhaust airflow rate using the flow rate specifications from the manufacturer.

2.6.3 Occupant Use of Mechanical Outdoor Air Systems

There were two types of systems encountered in the field study, ducted outdoor air (DOA) systems and heat recovery ventilator systems (HRV). The DOA systems are also sometimes called central fan integrated systems (CFI). The usages of the DOA systems, which are integrated with the FAU systems, were monitored as described below for the FAU systems. The usages of the HRV systems, which were either manually operated or operated off a timer, were recorded by the occupant on a log sheet. Typically the HRV systems operated continuously 24 hours per day.

2.6.4 Occupant Use of Nighttime Cooling Systems

There were two types of nighttime cooling systems encountered in the field study: whole house fan (WHF) systems and FAU return air damper (RAD) systems. The WHF systems consist of a large fan installed in the ceiling that draws outdoor air in by exhausting air from the home into the attic and subsequently to the outdoors through the attic vents. The usage of the WHF systems was monitored in a similar fashion to the FAU systems. The RAD systems have an automatic motorized damper integrated with the FAU return air duct that switches the air drawn into the FAU between the home air (i.e., from the central return air grille) and the outdoor air (i.e., from an outdoor air intake on the roof). The usage of the RAD systems was monitored using a relay and state logger combination. Magnetic tape or a zip-tie was used to secure the data logger with relay to the damper control and the lead wires were fastened with alligator clips to the damper 24 volts-direct current (VDC) motor wiring connections.

2.6.5 Occupant Use of Forced Air Heating/Cooling Systems (FAU)

The research team used ac-field data loggers to measure the FAU heating/cooling system operation. The data loggers were installed directly on the electrical wire for the fan with a zip-tie, and electrical tape if needed, for all FAUs in each home. The access panel to the furnace was removed in all cases to reach the electrical board for the forced air heating/cooling system. Airflow rates were measured at the return grill(s) using a balometer flow hood equipped with a 2 x 2-foot or 2 x 4-foot capture hood. The flow rate for those homes with a single fan dual zoned system with two fan speeds were measured with both thermostats in the ”fan-on” position, therefore, the highest fan flow rate was collected.

2.7 Outdoor Air Ventilation Measurements

2.7.1 Mechanically Supplied Outdoor Airflow Rates

Two different types of mechanical outdoor air systems were encountered in this field study: ducted outdoor air to the return side of the FAU (DOA systems) and heat recovery ventilators (HRV systems). In addition, there were other mechanical systems that provided outdoor air ventilation, directly or indirectly by exhaust, such as nighttime ventilation cooling systems (e.g., WHF, RAD), bathroom and kitchen exhaust fans, evaporative coolers, and window fans.

Ducted Outdoor Air Systems

There were two types of DOA systems encountered in the field study: those with manual dampers and those with automatic dampers and fan cyclers. Operation of the DOA systems with manual dampers is paired with operation of the FAU, so the usage was collected by the ac-field logger that monitored the FAU fan operation. The DOA systems with automatic dampers and fan cyclers were monitored using a relay and state logger combination. A magnetic tape or zip-tie was used to secure the data logger with relay to the damper control and lead wires were fastened with alligator clips to the damper 24 VDC motor wiring connections. The approach used to calculate the airflow rates of DOA systems was to measure the average air speed through the outdoor air duct with a velometer while the FAU is operating and then to determine the duct dimensions with a tape measure.

Heat Recovery Ventilators

Heat recovery ventilators are two-fan systems; typically one fan/duct system exhausts air from bathrooms and laundry/utility rooms to the outdoors, and another fan/duct system supplies outdoor air to the living space. The exhaust and outdoor air streams are ducted through an air-to-air heat exchanger so that the outdoor air is warmed by the exhaust air during the heating season and cooled by the exhaust air during the cooling season. The HRVs were typically operated continuously, and were therefore not monitored with either a data logger or written log. The homeowner was questioned by Team 1 about usage, and for those HRVs that were reported to be operated intermittently, either a written log or an ac-field data logger was installed using a zip-tie or tape to secure the data logger. The approach used to measure the airflow rates of HRVs was a balometer flow hood. The HRV outdoor airflow rates were measured at the single outdoor air supply air diffuser.

There were two types of nighttime cooling ventilation systems encountered in the field study: WHF systems and FAU RAD systems. The approach used to measure the airflow rates of the RAD systems was a balometer flow hood at the return air grill. The approach used to measure the airflow rates of the WHF systems was to measure the average air speed over the air intake in the home with a hot wire anemometer and multiply the air speed by the exhaust intake dimensions. This approach was used for the WHF systems rather than the balometer flow hood, because of the much higher airflow rates associated with the WHF systems.

There was also one home with a window fan consisting of a portable fan system that is inserted directly into window and one home with an evaporative cooling (EC) system. The EC system was separate from the FAU system and consisted of a roof mounted fan system that pulled outdoor air through evaporative cooling pads and delivered the air to a central supply air grille. The window fan system usage was monitored using written logs and the EC system usage was measured as described for the WHF systems. The airflow rates of the window fan system and the EC system were measured as described for the WHF systems.

2.7.2 Tracer Gas Measurements of Outdoor Air Exchange Rate

The outdoor air exchange rate in all the homes was measured with a tracer gas technique during the 24-hour air contaminant measurements and in a selection of homes for two-week period. This technique uses a passive constant injection of perfluorocarbon tracer (PFT). The tracer gas sources were placed by Field Team 1 at locations in each home approximately one week in advance of the tracer gas sampling, to allow for the emission rates of the sources to equilibrate. The number of sources and placement locations were determined for each home based on room volumes and layout to approximate a uniform indoor concentration. Since the emission rates from the PFT sources are temperature dependent, an air temperature data logger was deployed, located at the heating/cooling system thermostat, to log the air temperature at 15-minute intervals. These temperature data were then input into an equation of the emission rate as a function of time that was supplied by Brookhaven National Laboratory, the supplier of the PFT sources, to calculate the temperature-corrected PFT emission rates. The PFT used for these tests was perfluoromethylcyclohexane (PMCH).

The PFT samplers used for these tests were capillary adsorption tube samplers (CATS). These are small passive samplers that were co-located at the indoor air contaminant measurement site (e.g., family/living room) and were deployed by Field Team 2. The outdoor air exchange rate was calculated as described in ASTM E741 (ASTM 2000). For the 24-hour measurements, the samplers were collected by Field Team 3, but for the two-week measurements the samplers were collected by the homeowner, and returned by mail. A total of 25 homes had two-week PFT measurements.

The calculated method detection limit (MDL) in terms of air changes per hour of outdoor air and from the analyses of variance among the duplicate samples was 0.016 air changes per hour (ach).

In three 2-story homes, during the Winter North field session, additional CATS samplers were deployed in locations other than the air contaminant measurement site on the second floor (e.g., master bedroom, second floor bonus room) to evaluate the tracer gas concentration uniformity. In two of these three homes, a 24-hour measurement was collected during the same time as the CATS sampler at the air contaminant measurement site, and in one of these three homes a two-week measurement was collected during the same time as the CATS sampler at the air measurement contaminant site.

Since the blower door measurements conducted by Field Team 3 the day after the deployment of the PFT samplers by Field Team 2 would have a substantial and atypical impact on the home ventilation rate, the long-term PFT samplers were capped when we shut down the indoor air sampler before the blower door tests. The homeowners were then asked if they would uncap the long-term PFT sampler 48 hours later. Each of the homeowners was called to confirm that the samplers were uncapped, and then the homeowner collected the long-term PFT samplers, PFT sources, and temperature data logger approximately two weeks later. The homeowner used two mailing containers to return the CATs sampler and PFT sources separately at least a day apart.

The forms used to record these data were the House Dimensions/PFT Form, the Logger Form, the PFT Form, and the Air Sampling Tube Return Instructions. The home floor plan was also used by Team 1 to depict the locations of the PFT sources to assist Field Team 3 in retrieving the PFT sources and CAT samplers.

2.8 Indoor Air Quality Measurements

The following is a summary of the indoor air quality parameters that were measured in each home, with the exception of nitrogen dioxide and particulate matter ($PM_{2.5}$), which were only measured in 31 homes of the Winter North field session.

- Integrated Time Averaged IAQ Measurements
  - Volatile Organic Compounds (VOCs)
  - Formaldehyde and Acetaldehyde
  - Nitrogen Dioxide
  - Particulate Matter ($PM_{2.5}$)

- Real-Time IAQ Measurements
  - Carbon Monoxide
  - Carbon Dioxide
  - Temperature and Humidity

These IAQ parameters were measured for 22–26 hour period at one indoor location in the family/living room area of each of the homes. In addition, these IAQ parameters were also measured over the same time period at one outdoor location, in the backyard, for each cluster of two to three homes. The homes in each cluster were all within two miles of each other, with the exception of one cluster in the Summer North field session. This cluster had one home in Brentwood, which was 6.4 miles from the other two homes in Discovery Bay. Duplicate air samples were randomly selected to fulfill the 10% quality assurance and quality control requirement. The airflow rates for the integrated air samples were measured at the beginning and end of the sampling period using calibrated rotometers.

Special air samplers were developed to collect the integrated and real-time air contaminant concentrations. Figure 1 (page 44) is a photograph of the air sampler at an indoor site and Figure 2 (page 45) is a photograph of the air sampler at an outdoor site with the outdoor radiation/rain shield. For the integrated air samples, this air sampler consisted of a pair of air sampling pumps contained in an acoustically shielded fiberglass lock box mounted to a tripod. The study used SKC AirCheck 2000 air sampling pumps, which include an internal flow sensor that provides automatic electronic airflow control, such that the sample airflow rate is maintained within ± 5%, and 115 volts-alternating current (VAC) battery eliminators to allow operation over the proposed 24-hour sampling periods. One of these pumps provided the air sampling flow rate for the $PM_{2.5}$ air sampler. The second pump, through the use of a four-port manifold with low-flow control valves, provided the air sampling flow rate for the VOCs, nitrogen dioxide, and formaldehyde/acetaldehyde air samplers.

A power on-time meter provided a measurement of the time that 110 VAC power was supplied to the air sampler so that if there was a power interruption during the air sampling period the duration of the interruption would be known. The air sampling pumps automatically restart upon restoration of the power following a power interruption. In addition, a power cord restraint cover was installed at the connection of the power cord to the power receptacle to guard against inadvertent disconnection of the power cord plug from the receptacle.

For the real-time IAQ measurements, a TSI IAQ-Calc indoor air quality meter was mounted on the tripod next to the integrated air sampler manifold. The AC adaptor for the TSI IAQ-Calc was connected to a source of AC power inside of the fiberglass lock box. In addition, the TSI IAQ-Calc contained a parallel battery pack power supply that allows the instrument to continue operation upon a power interruption.

For the outdoor air sampler, a special rain/radiation shield was fabricated from galvanized sheet metal to enclose and protect the air samplers from rain and solar radiation. This rain/radiation shield has screened and louvered vents on two sides to allow circulation of outdoor air within the enclosed area.

The following is a detailed description of the air sampling and analytical techniques for each of the IAQ parameters.

2.8.1 Integrated Time Averaged IAQ Measurements (24-hour)

2.8.1.1 Volatile Organic Compounds

Volatile organic compounds other than formaldehyde and acetaldehyde were measured using methods based on U.S. EPA Method TO-17, "Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling onto Sorbent Tubes" (EPA 1999). This method involves drawing air at a constant rate with a pump through a multi-sorbent tube (i.e., Berkeley Analytical Associates sorbent tubes). The multi-sorbent tube consisted of a 3.5-inch (89-millimeter [mm]) long by ¼-inch (6.4-mm) outside diameter (OD) passivated stainless steel tube packed with two sorbent materials. The sorbent materials were 270 milligram (mg) Tenax TA™ 60/80 mesh backed up by 100 mg Carbosieve S-III™ 60/80 mesh. The samples were split 1:5 to prevent overloading of the analytical instrumentation and thermally desorbed and analyzed by gas chromatograph/mass spectrometry. The calculated MMDL from the analyses of variance among the replicate samples was between 2 and 5 nanograms (ng) for most compounds. Details of the analytical method and derivation of the method mass detection limit are summarized in Appendix B.

Samples were collected over a 24-hour period at a flow rate of approximately 10 cubic centimeters per minute (cc/min), which provided a method concentration detection limit of 0.1 $\mu g/m^3$ to 0.4 $\mu g/m^3$ for most compounds. Two samples were collected at each indoor and outdoor air sample location and one of each sample pair was submitted for analyses while the companion sampler was submitted as a backup sample.

Laboratory results for each sampler were corrected using the average of the field blanks for each batch of samplers that was submitted to the lab for analyses. For field blanks where the concentration was below the method detection limit of the instrumentation, a value equal to one-half the method detection limit concentration was used to calculate the average of the field blanks.

A total of 20 volatile organic compounds were selected by the ARB for quantification. These compounds were selected to include those with known indoor sources, those of known or suspected health concerns in indoor environments, and those with relevance to ARB programs.

2.8.1.2 Formaldehyde and Acetaldehyde

Formaldehyde and acetaldehyde concentrations were measured according to ASTM Standard D5197-03 (ASTM 2003c). This method involves drawing air at a constant rate with a pump through a solid sorbent cartridge (i.e., Waters Associates Sep-PAK silica gel impregnated with dinitrophenylhydrazine, DNPH). In addition, since ozone is known to interfere with this sample analyses, an ozone scrubber was installed directly upstream of the solid sorbent cartridge. This scrubber consists of a solid sorbent cartridge filled with granular potassium iodide (i.e., Waters Associates Sep-PAK Ozone Scrubber). Additionally, a scrubber (i.e., Anasorb CSC, coconut charcoal sorbent tube) was placed downstream of the sampler to scrub the emissions of residual acetonitrile released by the DNPH sample cartridge. The calculated MMDL from the analyses of variance among the replicate samples was 9 ng for both formaldehyde and acetaldehyde. Details of the analytical method and derivation of the MMDL are summarized in Appendix B.

Samples were collected over a 24-hour period at a flow rate of approximately 20 cc/min, which provided a concentration MDL of 0.3 $\mu g/m^3$ for formaldehyde and acetaldehyde. This concentration MDL is well below the California Environmental Protection Agency/Office of Environmental Health Hazard Assessment (Cal/EPA OEHHA) Chronic Inhalation Reference Exposure Levels (RELs) of 3 $\mu g/m^3$ for formaldehyde and 9 $\mu g/m^3$ for acetaldehyde (OEHHA 2003) and well below the ARB Indoor Air Quality Guideline of 33 $\mu g/m^3$ for formaldehyde (California Air Resources Board 2005).

Laboratory results for each sampler were corrected using the average of the field blanks for each batch of samplers that was submitted to the lab for analyses. For field blanks where the concentration was below the method detection limit a value equal to one-half the method detection limit concentration was used to calculate the average of the field blanks.

Measurements of the emission rates of formaldehyde from the FAU in three homes were also made. The impetus for these measurements, were some preliminary measurements conducted during warm months in some Arizona homes with FAUs located in attics (Davis 2004). In this study the investigator concluded that that the fiberglass inside of the

FAUs may be contributing to increased indoor concentrations of formaldehyde. Indeed the FAUs in the homes of this study contain a substantial amount of fiberglass soundliner, which may contain formaldehyde resins, and thus these materials may become substantial emitters of formaldehyde gas, especially when the materials are warm.

Measurements of emission rates were made by simultaneously measuring the concentration of formaldehyde in the supply and return air of the FAU as well as the attic air, where the FAUs were located, over a 30-minute period at a sample flow rate of approximately 950 cc/min. During these measurements the FAU fans were operated without cooling or heating. The supply air concentrations were measured at a supply air diffuser by inserting the sample inlet directly into the supply air diffuser. The return air concentrations were measured by inserting the sample inlet directly into the return air inlet. The attic air concentrations were measured in the attic at a location close to the attic access hatch, which was kept closed except to set the air sampler into the attic. The emission rates were calculated according to Equation 1 as the difference between the concentrations in the supply and return air streams times the FAU airflow rate.

$$E_{fau} = (C_{sa} - C_{ra})\ Q_{fau} \qquad \text{(EQ 1)}$$

where:

E_{fau} = emission rate from FAU (μg/h)

C_{sa} = concentration in the FAU supply air at the supply air diffuser (μg/m^3)

C_{ra} = concentration in the FAU return air at the return air inlet (μg/m^3)

Q_{fau} = airflow rate of the FAU (m^3/h)

This calculation assumes that the concentration of formaldehyde measured at the supply air diffuser represented the average concentration of the supply air delivered to the home and that the concentration measured at the return air inlet represented the average concentration of the return air leaving the home. While the latter is considered to be a reasonably good assumption, the assumption of uniform concentrations at all of the supply air diffusers is likely not nearly as good an assumption.

The emission rate of formaldehyde from the FAU was also compared to the total emission rate of formaldehyde into the home indoor air. The total home emission rate was calculated according to Equation 2 as the difference between the concentrations in the indoor air and the outdoor air times the outdoor air ventilation (calculated from the air exchange rate as determined by the PFT measurements and the home indoor air volume).

$$E_{home} = (C_i - C_o)\ \lambda_{pft}\ V \qquad \text{(EQ 2)}$$

where:

E_{home} = total home indoor emission rate from FAU (μg/h)

C_i = concentration in the indoor air (μg/m^3)

C_0 = concentration in the outdoor air (μg/m^3)

λ_{pft} = home outdoor air exchange rate determined from PFT measurement (h^{-1})

V = home indoor air volume (m^3)

This calculation assumes that the concentration of formaldehyde measured at the living room/dining room sampling location represented the average home indoor air concentration.

In addition to these FAU formaldehyde emission rate measurements, the air temperature and relative humidity in the attic air was also measured.

2.8.1.3 Nitrogen Dioxide

Nitrogen dioxide (NO_2) was measured following National Institute for Occupational Safety and Health (NIOSH) Method 6014 (NIOSH 1994a). This method involves drawing air at a constant rate with a pump through a two-stage solid-sorbent tube (i.e., SKC 226-40-02 molecular sieve impregnated with triethanolamine). The samplers were extracted and analyzed using spectrophotometry at a wavelength of 540 nanometers (nm). Both the front tube section and the back tube section were analyzed separately to verify that there was no significant breakthrough. The laboratory mass reporting limit of 0.8 μg was used for the MMDL.

Samples were collected over a 24-hour period at a flow rate of approximately 100 cc/min, which provided a concentration MDL of 5.7 μg/m^3. This concentration MDL is well below both the U. S. Environmental Protection Agency National Ambient Air Quality Standards (EPA NAAQS) (EPA 1990) standard of 100 μg/m^3 for an annual exposure, as well as the ARB Indoor Air Quality Guidelines (California Air Resources Board 2005) of 150 μg/m^3 for a 24-hour exposure.

Laboratory results for each sampler were corrected using the average of the field blanks for each batch of samplers that was submitted to the lab for analyses. For field blanks where the concentration was below the minimum mass reporting limit of the laboratory, a value of 0 μg was used to calculate the average of the field blanks.

2.8.1.4 Particulate Matter ($PM_{2.5}$)

Particulate matter ($PM_{2.5}$) was collected using gravimetric analyses according to NIOSH 500 (NIOSH 1994b). This method involves drawing air at a constant rate with a pump through a $PM_{2.5}$-size selective inlet (i.e., SKC 761-203 Personal Environmental Monitor) containing a 37 mm PTFE (i.e., Teflon) filter with a 2.0 µm pore size (i.e., SKC – 225-1709). Prior to and after sampling, the filters were equilibrated in a climate-controlled weighing room and analyzed gravimetrically. For the MMDL the research team used a MMDL of 5 µg, which is five times the 1 µg sensitivity of the microbalance.

Samples were collected over a 24-hour period at a flow rate of 2 liters per minute (L/min), which represents the design flow rate of the $PM_{2.5}$ impactor and provided a concentration MDL of 1.8 µg/m^3. This concentration MDL is well below both the EPA NAAQS (EPA 2007) ambient air quality standard of 35 µg/m^3 and the ARB Indoor Air Quality Guidelines (California Air Resources Board 2005) of 65 µg/m^3 for 24-hour exposures.

Laboratory results for each sampler were corrected using the average mass change of the field blanks for each batch of samplers that was submitted to the lab for analyses. For field blanks where the mass change was below the minimum MMDL of 5 µg, the actual reported mass change was used to calculate the average of the field blanks.

2.8.2 Real-Time IAQ Measurements

2.8.2.1 Carbon Monoxide

Carbon monoxide was measured with real-time instrumentation following EPA method IP-3A (EPA 1989) using an electrochemical sensor. We used a TSI IAQ-Calc meter, which incorporates a passive diffusive sample element and has built in data logging capabilities. The data logger was programmed to record carbon monoxide concentrations at one-minute intervals. The sensor has an accuracy of ± 3% or ± 3 parts per million (ppm), whichever is greater, a precision of ± 2% of reading, a resolution of 1 ppm, and a range of 0–500 ppm.

The concentration MDL was determined to be 0.8 ppm from analysis of the variance of the eight IAQ-calc instruments used for this field study. The eight instruments were co-located in a well-mixed test chamber with CO concentrations of 1 ppm to 2 ppm and the average of 60 one-minute consecutive measurements was used to determine the variance. The concentration MDL was calculated as the product of the standard deviation of the eight 60-minute average concentrations and the t-test value for a 95% confidence level (i.e., $t = 1.98$, $p = 0.05$, $df = 7$).

This concentration MDL is well below the ARB Indoor Air Quality Guideline (California Air Resources Board 2005) of 9 ppm for 8-hour exposures. The instrument was calibrated immediately prior to the start of sampling and checked following the sampling period, using zero and span (34 ppm) certified calibration gases. The sample data logged over the

24-hour period was corrected using the pre- and post-calibration curves and assuming that any changes in the calibrations occurred in a linear manner over time.

Prior to the commencement of the main field study and following a review of the Pilot Study data it was determined that the carbon monoxide sensors had a positive interference with water vapor of 2–4 ppm. This occurs only in outdoor air samples during periods of high relative humidity (i.e., greater than 75% and typically during rain events). No attempts have been made to correct these data, nor has any data been deleted where this effect appears to be occurring.

2.8.2.2 Carbon Dioxide

Carbon dioxide was measured with real-time instrumentation following EPA method IP-3A (EPA 1989) using non-dispersive infrared spectrophotometry (NDIR). A TSI IAQ-Calc meter, which incorporates a passive diffusive sample element and has built-in data logging capabilities, was used. The data logger was programmed to record carbon dioxide concentrations at one-minute intervals. The sensor has an accuracy of ± 3% or ± 50 ppm, whichever is greater; a resolution of 1 ppm; and a range of 0–5,000 ppm.

The concentration MDL was determined to be 24 ppm from analysis of the variance of the eight IAQ-calc instruments used for this field study. The eight instruments were co-located in a well-mixed test chamber with CO concentrations of 540 ppm to 570 ppm, and the average of 60 one-minute consecutive measurements was used to determine the variance. The concentration MDL was calculated as the product of the standard deviation of the eight 60-minute average concentrations and the t-test value for a 95% confidence level (i.e., $t = 1.98$, $p = 0.05$, $df = 7$).

This concentration MDL is well below both the ASHRAE (ASHRAE 2004b) body odor standard of 700 ppm over the outdoor concentration, which for typical outdoor concentrations of 350 to 450 ppm represents an indoor concentration of 1,050 to 1,150 ppm. The instrument was calibrated immediately prior to the start of sampling, and checked following the sampling period, using zero and span (1,035 ppm) certified calibration gases. The sample data logged over the 24-hour period was corrected using the pre- and post-calibrations curves and assuming that any changes in the calibrations occurred in a linear manner over time.

2.8.2.3 Temperature and Relative Humidity

Temperature and relative humidity were measured with real-time instrumentation using a thermistor sensor for air temperature and a thin-film capacitive sensor for relative humidity. A TSI IAQ-Calc meter, which has built in data-logging capabilities, was used. The data logger was programmed to record temperature and relative humidity at one-minute intervals. The temperature sensor has an accuracy of 1°F, a resolution of 0.1°F, and a range of 32°F–122°F. Prior to the field effort, the instruments' temperature sensors were compared to a certified mercury thermometer and the sample data logged over the 24-hour period was corrected using a single point correction. The relative humidity (RH) sensor has an accuracy of 3% RH, a resolution of 0.1% RH, and a range of 5%–95% RH. Prior to the field effort, the instruments' relative humidity sensors were compared with a laboratory probe that was calibrated with salt solutions according to ASTM E104-02 (ASTM 2002). The sample data points logged over the 24-hour period were corrected using a single point correction.

Meteorological data for the specific site of sampling were obtained from the nearest weather station listed by the National Climatic Data Center. The data included hourly wind speed and outdoor-air dry bulb temperature. Three weather stations were used for the northern California sites. The Sacramento Mather Airport was chosen; it is 13 miles northeast from the Elk Grove site, 12 miles northeast from the Sacramento site, 7 miles northwest from the Rancho Murieta site, 9 miles southwest from the El Dorado Hills site, and 10 miles southwest from the Folsom site. The second was the Stockton Metropolitan Airport, which is 23 miles east from the Brentwood sites, 18 miles east from the Discovery Bay sites, and 8 miles northwest from the Manteca sites. Finally the Auburn Municipal Airport was chosen for the Lincoln sites, which is 18 miles to the northeast.

Five weather stations were used for the Southern California sites. First was the Van Nuys Airport, which is 18 miles southeast of the Valencia sites, 15 miles southeast of the Santa Clarita sites, and 21 miles southeast from the Castaic sites. Second chosen was the Marine Corps Air Station-Miramar, which is 8 miles southeast from the San Diego sites and 6 miles southeast from San Marcos sites. Third chosen was the Naval Auxiliary Landing-Imperial Beach that is 5 miles southwest from the Chula Vista sites. Next, the Palmdale Regional Airport was chosen, which is 6 miles northeast of the Palmdale sites. Finally, the Riverside Municipal Airport was used, which is 13 miles southwest and northwest from the Fontana and Riverside sites, respectively.

2.9 Homeowner Source Activity

Homeowner activities potentially related to release of contaminants into the indoor air were recorded by the homeowner during the 24-hour IAQ measurement period using an indoor Source Activity Log, which was administered by Team 1 and collected by Team 3. The homeowner was asked to record the activity start times, duration, and type (e.g., cooking, cleaning, candle burning, dinner parties, barbecuing, leaf blowing, grass cutting) starting at 7:00 PM on the day before the 24-hour IAQ measurements and ending when Team 3 retrieved the forms. This results in up to a 48-hour time period when the homeowner recorded their source activities, with the first 12–20 hours being practice and which Team 2 checked, and the last 28–36 hours being the time period during which the 24-hour IAQ measurements were be collected for input into the database.

2.10 Homeowner IAQ/Ventilation Perceptions and Decision Factors

Perceptions regarding IAQ and ventilation were collected using the Occupant Questionnaire that was be administered to the homeowner by Team 1 and collected by Team 3. The Occupant Questionnaire was adapted from the UCB mail survey study. This questionnaire collected information regarding the homeowners' perception of activities that may affect IAQ in the home. Also included were key decision factors regarding home ventilation and purchasing ventilating equipment, building materials, air cleaners, and other products and materials that affect IAQ. The requested recall period was three weeks and the homeowners were instructed to complete the questionnaire following the start of the indoor air quality measurements by Team 3.

2.11 Quality Assurance and Quality Control

The October 10, 2005, Quality Assurance/Quality Control Plan (QA/QC Plan) was followed. The goal was to successfully collect and analyze a minimum of 98% of all field samples. For each of the integrated air contaminant measurements, VOCs, NO_2, formaldehyde/acetaldehyde, $PM_{2.5}$, and the PFT measurements the goal was to successfully collect and analyze a total of 10% field blanks and 10% field duplicates. In addition, for the PFT measurements the research team used three of the 10% duplicate samples for samples in a second zone of the home (i.e., the primary measurement zone was the living/dining room on the first floors and the second zone location was a second floor bedroom). The purpose of these two zone PFT measurements was to provide some data on the variation in the PFT indoor concentration, as the calculations of outdoor air exchange measurements from this measurement method assume that the indoor concentration of PFT is uniform through the home. In accordance with the QA/QC plan, the PFT sources and PFT samplers were stored and shipped separately to the field site.

Details of the QA/QC for the laboratory analyses of the VOCs, including formaldehyde and acetaldehyde, are discussed in Appendix B.

The QA/QC for the laboratory analyses of NO_2 and $PM_{2.5}$ were performed as described in the NIOSH Manual of Analytical Methods (NIOSH 1994a and 1994b).

For each VOC, an MDL was established based upon the variance observed in duplicate samples. The MDL was calculated to have greater than a 95% confidence that the measured value is greater than zero. This was calculated as the product of the standard deviation of the duplicate samples and the student's t-value $t_{0.095}$. For nitrogen dioxide, the laboratory mass reporting limit for the MDL was used, and for $PM_{2.5}$ an MDL equal to five times the sensitivity of the microbalance was used.

The flow rates for all integrated air samples utilizing sampling media (i.e., VOCs, aldehydes, nitrogen dioxide, and $PM_{2.5}$), were measured before and after the designated sample interval using rotometers, which were calibrated with a primary standard bubble meter or frictionless piston meter at the start of each sample season.

For the real-time measurements of carbon monoxide and carbon dioxide, these instruments were calibrated in the field at the start and end of each 24-hour sampling period utilizing certified bottled calibration gasses. Temperature sensors were calibrated with a NIST-certified mercury thermometer, and relative humidity sensors were calibrated with salt solutions at the start of each sample season.

Airflow rate devices (e.g., flow hoods) were calibrated using orifice plates at the start of each sample season. Pressure transducers for the building and duct leakage measurement devices (e.g., blower door and duct blaster) were calibrated with a primary standard micromanometer at the start of each sample season.

To assess the precision of the measurements of both the air contaminants and PFT measurements of outdoor air exchange rates, the 10% side-by-side duplicate samples were used. Then both the absolute precision and relative precision of each sample pair were calculated and summary statistics were prepared. The absolute precision was calculated as the absolute difference of the results of the sample pair. The relative precision was calculated as the relative standard deviation of the results of the sample pair. The relative precision is the more useful metric for assessing the precision, however, where the measured values are very low this calculation can result in inflated relative precision values. Thus in the case of high relative precision calculations it is useful to look at the absolute precisions. Low relative precisions always indicate good measurement precision. High relative precisions are only indicative of poor measurement precision if the absolute precision is also high.

2.12 Data Management and Analyses

For this study spreadsheets were created in Excel for all of the field data sheets contained in the SOPs that are detailed in our October 10, 2005, Quality Assurance/Quality Control Plan (QA/QC Plan). Hard copies of these field data sheets were taken into the field and used to record the data. The data on these hard copy field data sheets were then entered into identical electronic copy field data sheets. These Excel sheets contain all of the calibrations and calculations for converting the collected field data into the various ventilation and indoor air quality parameters. A minimum of 10% of each set of Excel field data sheets were compared with the corresponding hard copy field sheet for accuracy. If errors were identified, they were corrected and then another 10% of those data were checked in other field sheets. This process continued until no errors were found. In addition, the range of values was inspected for each variable, and for each variable that was unusually low or high the data sheets were inspected for errors, any errors observed were corrected, and then another 10% of those data were checked in other field sheets. This process continued until no errors were found. If a particular piece of data was found to be unusually low or high, and no error could be identified, then that piece of data was deleted.

A similar check of data in the ACCESS/SAS databases was conducted after the data were imported from the Excel data sheets. For each variable a 10% data check was conducted, and data that was incorrect was corrected, as described for the Excel datasheets.

Unless specified otherwise, the results and associated population statistics are based upon the "All Home" sample frame of 108 homes, which is summarized in Appendix C. The complete list of all home season-region tests is summarized in Appendix D. The "All Home" sample frame was constructed to provide a sample base for producing the population statistics without having a home represented more than once and to provide a balance between the North and South regions and the summer and winter seasons. The fall swing season tests were excluded from this sample frame. The 10 seasonal repeat North homes and 10 seasonal repeat South homes were randomly selected and evenly split into the summer and winter field sessions. The first test day contaminant concentration and outdoor air exchange rate data were selected for the four multi-day test homes.

Appendix E contains for each home the following data; the results of the indoor and outdoor air contaminant measurements, the indoor and outdoor temperature and relative humidity measurements, and the outdoor air exchange rate PFT measurements.

Appendix F contains for each home the following data; home characteristics, including building envelope air leakage and duct leakage measurements, window usage, mechanical and outdoor air exhaust air exchange rate measurements, and characteristics of the mechanical outdoor air ventilation systems.

The indoor emission rates of VOCs were calculated according to Equation 3, as the difference between the concentrations in the indoor air and the outdoor air times the outdoor air exchange rate (as determined by the PFT measurements).

$$E_v = (C_i - C_o)\ \lambda_{pft} \qquad \text{(EQ 3)}$$

where:

E_v = total volume specific indoor emission rate into home ($\mu g/m^3$-h)

C_i = concentration in the indoor air ($\mu g/m^3$)

C_0 = concentration in the outdoor air ($\mu g/m^3$)

λ_{pft} = home outdoor air exchange rate determined from PFT measurement (h^{-1})

This calculation assumes that the penetration factor of VOCs in the outdoor air that is infiltrating through the building envelope was 1.0 and that there was no removal of VOCs from the indoor air unrelated to the outdoor air exchange rate (e.g., surface deposition/surface reaction, indoor air reactions, air filtration). The research team feels that these are relatively valid assumptions for the VOCs reported here. In addition, this calculation assumes that that the concentration of VOCs measured at the living room/ dining room sampling location represented the average home indoor air concentration.

No emission rates were calculated for homes where both the indoor and outdoor concentrations were less than the method detection limit concentration. For homes where either the indoor or outdoor concentration was below the method detection limit concentration, the calculation was performed utilizing a concentration of one half the MDL concentration.

It is important to note these emission rates are different than the home emission rates of formaldehyde that were described in Section 2.8.1.2 and calculated according to Equation 2. Those emission rate calculations are total emission rates of formaldehyde into the home indoor air and are expressed in units of micrograms per hour (μg/h). The emission rates described above, and calculated according to Equation 3, are the volume-specific emission rates that are the emission rates normalized by the indoor air volume of the home. These volume-specific emission rates are useful when comparing emission rates between different homes, since larger homes have larger areas from which indoor air contaminants can be emitted.

Several group comparisons for indoor air contaminants, outdoor air exchange rates, and window usage were also performed. These group comparisons included North versus South homes, summer versus. winter repeat homes, and homes with and without mechanical outdoor air ventilation systems. For these comparisons, t-tests were used to test the hypothesis that there is no difference between the mean values of two different sample populations. A two-tailed t-test was used for two samples with unequal variance to determine the probability that the mean of the two sample groups were not different for the comparisons of North versus South homes and homes with and without mechanical outdoor air ventilation systems. For the comparison of summer versus winter repeat homes, a paired t-test was used. For each of these comparisons the probability that the difference between the means was not different was calculated. If the probability of no difference was less than 0.05, then the difference between the means was deemed significant.

Because t-tests require that sample populations be normally distributed, the Kolmogorov-Smirnov (K-S) statistic, as programmed in the SAS Univariate procedure, was used to test whether the distributions of variables being compared were normal. The Kolmogorov-Smirnov null hypothesis is that the distribution is normal. If the K-S statistic returned a result with a probability of less than 0.05, then the distribution was determined to not be normal. If the sample population was determined to not be normal, then a transformation was applied to the sample, beginning with a log transformation. If the log transformation did not produce normal data then other transformations were tried, including inverse, squared, and square root transformations until a transformation that was normal was identified.

Correlation analyses between selected indoor air contaminants and house characteristics and environmental factors were also prepared. For these analyses the Pearson correlation method was used to test for the strength and direction of a linear relationship between pairs of variables. Because these analyses require that sample populations be normally distributed, the data were normalized as described above. The research team also prepared Spearman correlation analyses, which do not require the sample populations be normally distributed.

Figure 1. Quiet indoor air sampler for formaldehyde, VOCs, $PM_{2.5}$, NO_2, CO, CO_2, temperature, and relative humidity, typically installed in a home living/dining room area for a 22–26 hour sampling period.

Figure 2. Outdoor air sampler for formaldehyde, VOCs, $PM_{2.5}$, NO_2, CO, CO_2, temperature, and relative humidity, with outdoor radiation/rain shield.

3.0 Project Outcomes/Results and Discussion

3.1 Quality Assurance and Quality Control

Table 2 (page 145) contains a summary of the percentages of air contaminant and PFT field samples, blanks, and duplicates that were successfully collected and analyzed along with the goals in the QA/QC plan.

With respect to the percentage of field samples successfully collected and analyzed, the study's goal of a minimum of 98% was met, with the exception of the formaldehyde/acetaldehyde samples, where the percentage successfully collected and analyzed was 96%.

With respect to the percentage of field sample blanks successfully collected and analyzed, the goal of a minimum of 10% of the total field samples successfully collected and analyzed (i.e., less field blanks and duplicates) was met.

With respect to the percentage of field sample duplicates successfully collected and analyzed, the study's goal of a minimum of 10% of the total field samples successfully collected and analyzed (i.e., less field blanks and duplicates) was met, with the exception of the formaldehyde/acetaldehyde and carbon monoxide samples, where the percentages successfully collected and analyzed were 9%.

Details on the sample and/or analyses failures can be found in Appendix G Difficulties Encountered in the Field, which summarizes the difficulties encountered during the study, followed by the corrective action that was taken. For the population statistics discussed in this section, unless otherwise noted, the following samples were deleted: those that had shortened sample periods (thus not representative of the standard 24-hour samples), those with failed analytical analyses, or those that yielded unrealistic data.

The results of the sample blank analyses for VOCs, including formaldehyde and acetaldehyde, are summarized separately in Tables 3, 4, 5, and 6 (pages 146–149) for the Summer-North, Summer-South, Winter-North, and Winter-South field sessions respectively. The average field blank masses were calculated separately for each field sessions and subtracted from the field sample masses for that field session. If the mass of a field blank was below the method mass detection limit (MMDL) then a value of one half of the MMDL was used to calculate the average field blank mass.

For the 18 VOC blank samples, just six of the 20 compounds analyzed had masses exceeding the MMDL; phenol (6 samples), styrene (3 samples), hexanal (2 samples), d-limonene (1 sample), 1,2,4 trimethylbenzene (1 sample), and naphthalene (1 sample). The compound with most field blank concentrations exceeding the MMDL, phenol, had field blank mass concentrations that ranged from 3.3 ng to 24 ng, with an average of 7.9 ng

(MMDL 2.8 ng). The ratio of the average field blank mass to the MMDL for phenol was less than 1.0 for all field sessions except for the Summer South field session, where the ratio was 3.1. The only other compounds with ratios of the average field blank mass to the MMDL that exceeded 1.0 were styrene (with a ratio of 1.5 for the Summer South field session) and hexanal (with a ratio of 1.4 for the Winter South field session).

For the 19 aldehyde blank samples, 10 had masses exceeding the MMDL for acetaldehyde and 5 had masses exceeding the MMDL for formaldehyde. For acetaldehyde, the field blank mass concentrations ranged from 9.4 ng to 49 ng with an average of 20 ng (MMDL 9.0 ng). The ratio of the average field blank mass to the MMDL for acetaldehyde ranged from 1.1 for the Winter North field session to 2.1 for the Summer North field session and was less than 1.0 in the Winter South field session. For formaldehyde, the field blank mass concentrations ranged from 10 ng to 22 ng, with an average of 15 ng (MMDL 9.0 ng). The ratio of the average field blank mass to the MMDL for formaldehyde was less than 1.0 in each of the field sessions.

The results of the VOC sample duplicate analyses, including formaldehyde and acetaldehyde, are summarized in Table 7 (page 150). The mean absolute precision ranged from 0.003 $\mu g/m^3$ for 1,4-dichlorobenxene to 4.0 $\mu g/m^3$ for formaldehyde. The mean relative precision ranged from 0.01 for 1,4-dichlorobenzene to 0.27 for styrene.

The results of the sample blank analyses for nitrogen dioxide and $PM_{2.5}$ particulate matter are summarized in Table 8 (page 151). For these two air contaminants, which were only sampled during the Winter North field session, the samples were analyzed in three batches; one for each of the three weeks of the field session. For the nitrogen dioxide field blanks, if the field blank mass was below the MMDL of 0.8 µg, a mass of zero was used to calculate the average of the field blanks. For $PM_{2.5}$, the average mass of the field blanks was calculated directly from the measured masses of the field blanks. There were a total of five field blanks each for nitrogen dioxide and $PM_{2.5}$ particulate matter. The five nitrogen dioxide field blanks were all below the MMDL for an average field blank mass of zero for each of the three sample weeks. The five $PM_{2.5}$ particulate matter field blanks ranged from -1 to -3 µg, with an average field blank mass of -2 µg for Week 1 and Week 2 and -3 µg for week 3.

The results of the carbon monoxide, carbon dioxide, nitrogen dioxide, and $PM_{2.5}$ particulate matter sample pair duplicate analyses are summarized in Table 9 (page 152). The mean absolute precision for nitrogen dioxide was 0.2 $\mu g/m^3$ and the mean relative precision was 0.02. The mean absolute precision for $PM_{2.5}$ particulate matter was 2.0 $\mu g/m^3$, and the mean relative precision was 0.11. The mean absolute precision for carbon monoxide was 0.6 ppm and the mean relative precision was 0.53. The mean absolute precision for carbon dioxide was 16 ppm and the mean relative precision was 0.02.

The results of the sample blank analyses for the PFT samples for the outdoor air exchange rate measurements are summarized in Table 10 (page 153). The PFT samples were analyzed in three batches, Summer-1, for the first 12 homes of the Summer-North field session, Summer-2, for the remainder of the Summer-North homes and all of the Summer-South homes, and Winter, for all of the Winter-North and Winter-South homes. There were a total of 16 field blanks analyzed. The percentage of field blank to field samples ranged from 6% to 11% for the three laboratory analyses sessions. More field blank samples were added to the Winter field session when it was determined that more were required to meet the 10% required by the QA/QC plan.

A total of 13 of the 16 field blanks were above the Method Volume Detection Limit (MVDL) of 0.001 picoliters (pL), and ranged from 0.009 pL to 0.043 pL. The impact of the variance in the field blank analyses is minimal, since the amount of tracer that the samplers collect is so much larger than contained in the blanks. This is especially true for homes with low outdoor air exchange rates.

For example, Home 025 had an outdoor air exchange rate of 0.35 ach based upon the 6.356 pL of tracer collected by the sampler less the average of 0.017 pL for that batch of field sample blanks. If it is assumed that the true amount of tracer in the sample prior to sampling ranges from 0 pL to the maximum observed field blank amount of 0.043 pL, the calculated outdoor air exchange rate ranges differ by less than 0.2%. For homes with very high air exchange rates, and consequently less tracer collected by the sampler, the impact of the blank correction to the analyses can be more substantial. For example, Home 014 had an outdoor air exchange rate of 5.3 ach based upon the 0.347 pL of tracer collected by the sampler less the average of 0.013 pL for that batch of field sample blanks. If it is assumed that the true amount of tracer in the sample prior to sampling ranges from 0 pL to the maximum observed field blank amount of 0.043 pL, the calculated outdoor air exchange rate ranges differ by about 8% (e.g., 5.1–5.9 ach).

The results of the PFT outdoor air exchange rate measurement sample pair duplicate analyses are summarized in Table 11 (page 154). The mean absolute precision for the 24-hour measurements was 0.01 ach, and the mean relative precision was 0.02. The mean absolute precision for the two-week measurements was 0.01 ach, and the mean relative precision was 0.01.

The research team also compared the PFT measurements of outdoor air exchange rates in three 2-story homes where the outdoor air exchange rate was measured at two locations; one in the usual first floor living/dining room area and one at a second location on the second floor. The purpose of these two zone PFT measurements was to provide some data on the variation in the PFT indoor concentration, because the calculations of outdoor air exchange measurements from this measurement method assume that the indoor concentration of PFT is uniform through the home. The results of these measurements are presented in Table 12 (page 155), along with the number of hours that the FAU operated and the square foot-hours (ft^2-hrs) of window opening. The absolute precision of the two PFT measurements ranged from 0.01 ach in Home 019 and Home 099 to 0.06 ach in Home 116. The relative precision of the two PFT measurements ranged from 0.05 in Home 099 to 0.22 in Home 116.

While the research team only had two-zone measurements in three homes, these measurements indicated that the differences between the two PFT measurements were relatively small and that the air in the homes was well mixed. Home 116, which had the highest difference in the two PFT measurements, had no operation hours of the FAU and 50.5 ft^2-hrs of window usage, both of which are factors that are not conducive to good mixing of the indoor air. Thus, even in this home with factors not conducive to good mixing of the indoor air, the difference between the 2 PFT measurements of outdoor air exchange was moderate (i.e., 0.22 ach versus 0.16 ach).

3.2 Home Selection and Recruitment

The home recruitment response rate for each region-season is summarized in Table 13 (page 156). For the summer field session, a total 1,358 recruitment letters were mailed to new single-family detached homes in Northern California, of which 340 were to UCB mailer respondents and 1,018 were to additional sample. Researchers mailed 1,408 recruitment letters to new single-family detached homes in Southern California, of which 329 were to UCB mailer respondents and 1,079 were to an additional sample. The percentage of homeowners sent recruitment letters that called to say they were interested in participating in the field study ranged from 3% to 7% for the summer and winter recruitment sessions.

Clusters were then established for those homes based on their relative distance, and on which of the three inspection times each home noted as being required or preferred. Homes were clustered into groups of 2–3 homes with one outdoor air sampling location for each cluster.

Recruitment was begun in geographic areas where the most calls from homeowners interested in participating in the field study had been received. Efforts were also made to reach out by telephone to homeowners in the same areas who had not called in to express interest, favoring UCB mailer respondents over the additional sample. Four percent of both the UCB respondents and additional sample who had received the mailers refused to participate. One percent of the UCB respondents and less than 1% of additional sample who had received mailers were disqualified (renters, smokers, home built before 2002). Due to the geographical constraints of the study and the location of some homes, a few willing homeowners could not be included in the study (5% of the mailers to UCB respondents and 2% of the mailers to the additional sample). Due to scheduling constraints some homeowners had time conflicts and could not participate (1% of the mailers to UCB respondents and 2% of the mailers to the additional sample).

Overall, 827 phone calls were made to 471 homes in Northern California to recruit 32 homes (25.8 calls per recruited home). The research team made 429 phone calls to 201 homes in Southern California to recruit 31 homes (13.8 calls per recruited home).

Between August 7 and August 25, 2006, field measurements were scheduled for a total of 32 Northern California homes, our target for the three-week Summer North field session. Of these, 17 (53%) were UCB mailer respondents and 15 were from the additional sample. Week 1 consisted of 11 homes: 9 in Brentwood and 2 in Discovery Bay; Week 2 consisted of 12 homes: 9 in Elk Grove and 3 in Sacramento; and Week 3 consisted of 9 homes: 3 in Elk Grove, 4 in Manteca, and 2 in Rancho Murrieta.

There were a total of 18 mechanically ventilated homes in the 32-home sample, including 4 with nighttime ventilation cooling systems.

Between September 5 and September 22, 2006, field measurements were scheduled for a total of 31 homes—one home short of the 32-home target for the three-week Summer South field session. Of these, 17 (55%) were UCB mailer respondents and 14 were additional sample. Week 1 consisted of 12 homes: 3 in Valencia, 3 in Castaic, 3 in Santa Clarita, and 3 in Canyon Country; Week 2 consisted of 8 homes: 2 in Chula Vista, 4 in San Diego, and 2 in San Marcos; Week 3 consisted of 11 homes: 2 in Castaic, 3 in Santa Clarita, and 6 in Palmdale.

There were a total of 4 mechanically ventilated homes in the 31-home sample, including 1 with a nighttime ventilation cooling system and one with an evaporative cooling system.

The fall swing season study targeted the re-testing of four naturally ventilated homes in Northern California. Recruitment letters were mailed to the 15 of the 32 Summer participants Northern California who had naturally ventilated homes, and they were asked to participate in a new series of tests in the fall swing season. Ten homeowners (67% of the mailers) replied that they were interested in participating. One homeowner was not interested, one homeowner was not able to participate within the timeframe suggested, and three never replied and could not be contacted by telephone.

On October 16 and 17, 2006, field measurements were scheduled in two clusters: 2 in Discovery Bay and 2 in Brentwood. One home in Discovery Bay and one home in Brentwood were UCB mailer respondents.

The inter Study targeted re-testing of 10 homes each in Northern and Southern California. A total 1,500 recruitment letters were mailed to new single-family detached homes in Northern California, of which 177 were to UCB mailer respondents and 1,323 were to an additional sample. The research team mailed 1,486 recruitment letters to new single-family detached homes in Southern California, of which 313 were to the UCB mailer sample and 1,173 were to the additional sample. Each of these mailers included all the participants from the Summer season. Again, homeowners were asked to call back if they were willing to participate in the study. A total of 71 Northern California homeowners (5% of the mailer) and 62 Southern California homeowners (4% of the mailer) called in to state they were interested in the study.

Recruitment started in geographic areas from which most calls from homeowners interested in participating in the study had been received. The research team also reached out by telephone to homeowners in the same areas who had not called in to express interest, favoring UCB mailer respondents over the additional sample. Less than 1% of the UCB respondents and 1% of the additional sample who were contacted by phone refused to participate. Less than 1% of both the UCB respondents and of the additional sample who had received mailers were disqualified (e.g., renters, smokers, home vintage before 2002). Due to the geographical constraints of the study and the location of some homes, a few willing homeowners could not be included in the study (3% of the mailers to UCB respondents and less than 1% of the mailers to additional sample). Due to scheduling constraints some willing homeowners had conflicts and could not participate (1% of the mailers to both UCB respondents and to the additional sample).

Overall, 385 phone calls were made to 264 homes in Southern California to recruit 33 homes (11.6 calls per recruited home). The research team made 158 phone calls to 73 homes in Northern California to recruit 33 homes (4.8 calls per recruited home). Two factors contributed to the higher success rate in the winter recruitment: 10 homes in each region were repeat participants and due to the geographic constraints of the study, the location of the 10 repeat homes dictated the location of the other homes that had to be recruited. Consequently, the effort of recruiting and scheduling 24 additional homes in the North and 23 additional homes in the South was much reduced as compared to the Summer recruitment.

Between January 16 and February 1, 2007, field measurements were scheduled for a total of 33 homes in Southern California—one more than the 32-home target for the three-week Winter South field session. Of these, 12 (36%) were UCB mailer respondents and 21 were additional sample. Of the 33 homes, 10 had also participated in the Summer Study (8 UCB mailer respondents and 2 additional sample). Week 1 consisted of 11 homes: 5 in Santa Clarita, 3 in Valencia, and 3 in Castaic; Week 2 consisted of 11 homes: 5 in San Marcos, 3 in Chula Vista, and 3 in San Diego; Week 3 consisted of 11 homes: 8 in Fontana, and 3 in Riverside.

There were a total of four mechanically ventilated homes in the 33-home sample, including two with nighttime ventilation cooling systems.

Between February 12 and March 1, 2007, field measurements were scheduled for a total of 32 Northern California homes, our target for the three-week Winter North field session. Of these, 10 (31%) were UCB respondents and 22 were from the additional sample. Of the 32 homes, 10 homes were previous Summer participants (6 UCB mailer respondents and 4 from the additional sample). Three of the 10 repeat homes were fall participants as well. Week 1 consisted of 12 homes: 6 in Elk Grove and 6 in Sacramento; Week 2 consisted of 12 homes: 3 in Discovery Bay, 3 in Stockton and 6 in Brentwood; and Week 3 consisted of 10 homes: 5 in El Dorado Hills, 3 in Lincoln and Lincoln Hills, and 2 in Folsom.

There were a total of 17 mechanically ventilated homes in the 32-home sample, including 5 with nighttime ventilation cooling systems.

The following is the breakdown of the recruited sample set. No-mechanical outdoor air homes are defined as those homes without either a mechanical outdoor air supply system or a nighttime cooling system.

<u>Summer-North</u>
32 homes
18 mechanical outdoor air (including 4 with nighttime ventilation cooling systems)
14 non-mechanical outdoor air
1 multi-day home (Thursday-Friday, Friday-Saturday, Saturday-Sunday)

<u>Summer-South</u>
31 homes
4 mechanical outdoor air (including 1 with a nighttime ventilation cooling system)

28 non-mechanical outdoor air
1 multi-day home (Thursday–Friday, Friday–Saturday, Saturday–Sunday)

<u>Winter-North</u>
32 homes
17 mechanical outdoor air (including 5 with nighttime ventilation cooling systems)

15 non-mechanical outdoor air
1 multi-day home (Thursday–Friday, Friday–Saturday, Saturday–Sunday)
10 seasonal repeats from Summer (i.e., 22 new homes)

<u>Winter-South</u>
33 homes
4 mechanical outdoor air (including 1 with a nighttime ventilation cooling system)
29 non-mechanical outdoor air
1 multi-day home (Thursday–Friday, Friday–Saturday, Saturday–Sunday)
10 seasonal repeats from Summer (i.e., 23 new homes)

Figure 3 (page 102) is a map of the State of California, depicting the locations of homes for the summer and winter 2006–2007 field sessions in Northern and Southern California.

A total of 58 (44%) of the 132 home tests, including seasonal repeat tests, were recruited from the UCB mail survey. Excluding seasonal repeats, a total of 42 (39%) of the 108 homes were recruited from the UCB mail survey.

As can be seen from Table 13, the Summer recruitment substantially depleted the potential participants from the UCB mail survey, and while 53% and 55% of the Summer homes were recruited from the UCB mail survey for the North and South regions respectively, only 36% and 31% were recruited from the Winter North and South regions, respectively.

Thus, the study met the primary selection criteria of 54 homes in the North, 54 homes in the South, a minimum of 20 homes with mechanical outdoor air systems, 20 seasonal crossover homes, and 4 multi-day homes.

With respect to the secondary selection criteria requested by the ARB and Energy Commission, the study was constrained by the lack of sufficient excess sample, as well as the geographical constraints required for clustering of homes, to completely fulfill all of these requirements. Homes were excluded in the San Jose and San Francisco Bay areas. In addition, 6 homes in Palmdale were recruited for the high desert area, and for the ARB concurrent acrylonitrile air testing, 3 homes were recruited from Chula Vista. The research team was not able to completely avoid selecting homes in the Southern California Coastal areas, and so included 7 homes in the San Diego area and 4 homes in the San Marcos area.

With respect to the secondary selection criteria of matching the sample percentages from the UCB mail survey, Table 14 (page 157) presents this comparison for the three geographical strata in the UCB mail survey: Sacramento/Delta, Southern California Coastal, and Rest-of-State. While the field sample is in relatively close agreement to the UCB mail survey sample for the percentage of homes in the Southern California geographical strata, 16% and 21% respectively, the percentage of homes in the field study is over-represented in the Sacramento/Delta region (i.e., 39% and 21%, respectively) and under-represented in the Rest-of-State region (i.e., 45% and 58%, respectively). One of the reasons it was difficult to more closely achieve a match of the geographical strata distributions between the field study and UCB mail survey study was that the study plan required 50% of the homes to be in the North and 50% in the South, while the UCB mail survey contained only 28% in the North and 72% in the South.

Although the UCB mail survey sample, upon which the sample selection was largely but not entirely based, was a stratified random sample, the results in this study have not been weighted to adjust for that stratification or other selection factors.

3.3 Home and Site Characteristics Collection

The home and site characteristics were collected on-site by the field teams and reported by occupants on questionnaires. The data collected for these characteristics are summarized in Tables 15, 16, 17, 18, 19, 20, and 21 (pages 158–164).

The 108 homes recruited for the summer, fall and winter field sessions were primarily from track developments by production builders, were built in 2002 or later, and have been owner-occupied for at least one year. As summarized in Table 15, the median age of the homes was 3.4 years, with a range of 1.7 years to 5.5 years. The median square footage was 2,703 square feet (ft^2), with a range of 1,283 ft^2 to 5,064 ft^2. The total median composite wood loading was 925 ft^2, with a minimum of 263 ft^2 and a maximum of 2,925 ft^2. Most of the composite wood came from furniture and cabinetry, with none from wall or ceiling finishes and only one home with 979 ft^2 of a floor finish made from composite wood.

As summarized in Table 16, a total of 97% of the homes had slab-on-grade foundations and 99% had attached garages. A total of 60% of the homes had attached garages with living spaces above the garage, which is a configuration with a stronger potential for transport of garage air contaminants into the home indoor air than attached garages without living spaces located above.

A total of 99% of the homes had attics. The exterior envelope was typically stucco. All homes had FAU heating systems, 94% of which, also had cooling capabilities, and all but one, which was located in the garage, were located in the attic. The kitchen cooking ranges consisted of 2% gas ranges and 98% electric ranges. A total of 85% of the cooking ranges had exhaust fans ducted to outdoors. The kitchen ovens consisted of 27% gas ovens and 73% electric ovens. Only 2% of the ovens had exhaust fans ducted to outdoors. The clothes dryers consisted of 76% gas dryers and 24% electric dryers, with 98% with exhaust ducted to outdoors and 11% with exhaust leaks. All of the FAUs were gas-fired heaters; there were no homes with electric heat. All of the FAU t-stats had the fan switch set in the auto position, which operates the fan only when the t-stat calls for heating or cooling. The water heaters consisted of 98% gas heaters and 2% electric heaters. There were no window air conditioning units. There were a total of 61% homes with decorative gas log fireplaces that were vented to the outdoors and a total of 31% sealed combustion fireplaces vented to the outdoors. There were no unvented gas log fireplaces. The field team inspectors reported an odor upon entry to the home in 27% of the homes.

As summarized in Table 17, the primary kitchen cabinetry consisted of 97% with composite wood with laminate, 2% composite wood with no laminate, and 1% solid wood cabinetry. The primary bathroom cabinetry consisted of 99% with composite wood with laminate, 1% composite wood with no laminate, and none with solid wood cabinetry. The overall cleanliness of the homes, was rated by the field team inspectors as “Very Clean” in 72% of the homes, and the overall home clutter was rated as “No Clutter” in 49% of the homes and "Some Clutter" in 41% of the homes. Outdoor contaminant sources within 500 feet of the home, were observed by the field team in 55% of the homes. The three outdoor sources most frequently encountered were gas station at 13% of the homes, and restaurants or open field crops at 8% of the homes

As summarized in Table 18, a total of 73% of the homes reported having two adults living in the home, with 8% having just one adult and 1% having 5 adults. A total of 46% of the homes reported having no children under 18 living in the home, with 25% having two children and 1% having 5 children. Only 3% of the homeowners reported having one or more occupants that smoke in the home, and as per our recruitment criteria these smokers reported that they do not smoke in the home. A total of 56% of the homes reported having pets that live in the home, and 57% of the homeowners reported wearing shoes in the home. A total of 16% of the homeowners reported cloths or drapes that had been dry-cleaned within the last week prior to the air testing date.

As summarized in Table 19, homeowners reported that within the last 6 months (3 months for homes with seasonal repeat tests), a number of potentially air contaminant-generating indoor activities. The three activities reported most frequently were: pesticide applications in 42% of the homes, painting in 32% of the homes, and new furniture installed in 22% of the homes. No homeowners reported and fire/smoke damage, and 6% reported mold or moisture damage.

The homeowners reported use of portable air cleaners in 17% of the homes. This percentage compares to approximately 15% of California homeowners reporting that they used a portable air cleaner, as determined from the statewide probability sample in the UCB mail survey (Price et al. 2007). In a telephone survey of 2,019 California households, approximately 14% reported they either owned or used a portable air cleaner in the past five years (Piazza et al. 2007).

The homeowners also reported use of plug-in air fresheners in 33% of the homes, candles in 58% of the homes, incense in 11% of the homes, and mothballs in 7% of the homes. A total of 28% of the homeowners reported activities associated with hobbies and crafts in their homes. With respect to storage of materials in the home or garage that are potential sources of indoor air contaminants, homeowners reported storage of various products with a frequency of 61% of the homes for latex products to 100% of the homes for cleaning supplies. A total of 92% of the homeowners reported storing motor vehicles in the garage.

As summarized in Table 20, a total of 13% of the homeowners reported vacuuming the carpets and rugs in the most heavily used rooms "twice per week or more often", while 5% reported vacuuming "less than every 3–4 weeks." In addition, 37% of the homeowners reported steam cleaning of carpets, 16% reported professional dry cleaning, and 63% reported spot cleaning or dry cleaning by the homeowner. With respect to problems encountered in the home since they began occupancy the most frequently reported conditions were: wall or window leaks in 13% of the homes, plumbing leaks in 10% of the homes, other unpleasant odors in 7% of the homes, and other moisture problems in 7% of the homes.

The types of mechanical outdoor air systems and controls observed in the field study are summarized in Table 21. There were a total of 36 of the 108 homes (33%) with one or more type of mechanical outdoor air systems. These included 17 homes (16%), with only a DOA system, 12 homes (11%) with nighttime cooling systems (i.e., either whole house fans, WHF, or FAU return air damper (RAD) systems, 6 homes (6%) with only an HRV system, 5 homes (4%) with multiple mechanical outdoor air systems, and one home (1%) with an evaporative cooling system. There were a total of 40 mechanical outdoor air ventilation systems in the 36 homes with these type systems, with DOA systems comprising 43% and HRV systems comprising 23%.

The type of damper controls included 30% manual, typically found with some DOA systems, 33% automatic, typically found with some DOA and the RAD systems, 13% gravity, typically found with the WHF systems, and 25% no damper, typically found with the HRV systems.

The type of operation control types included: 45% controlled with the FAU thermostat, typically found with the DOA and RAD systems; 33% controlled with an on/off switch, typically found with HRV systems; 18% with an FAU fan cycler, typically found with some DOA systems; and 5% controlled by a timer, typically found with some HRV systems. The location of the controls were in the home (i.e., accessible) in 75% of the homes, and in the attic (inaccessible) in 25% of the homes, typically found with HRV systems.

3.4 Home Air Leakage Measurements

3.4.1 Forced Air Heating/Cooling System Duct Leakage

The forced air heating/cooling (FAU) system duct leakage area, as calculated from the duct pressurization tests, is expressed as the percent of the total forced air heating/cooling system flowrate and is summarized in Table 22 (page 165). Figure 4 (page 103) is the cumulative frequency distribution of the measured FAU duct leakage percentage. These measurements are compared to the California Title 24 (California Energy Commission 2001a) requirement of 6%. The home FAU system leakage had a median of 10% that ranged from 1.9% to 73%. A total of 116 of the 138 systems (86%) had percentages exceeding the California Title 24 maximum of 6%. The median ratio of the measured duct leakage percentage to the maximum 6% requirement, for those homes exceeding 6% duct leakage, was 1.7.

There were a total of 8 homes with duct leakage percentages exceeding 28%, which represents 2.8 times the median of 10%. Four of these nine homes had mechanical outdoor air ventilation systems integrated into the FAU system and included one DOA systems and three RAD systems. The additional ducting associated with these systems is believed to contribute to the higher duct leakage. In particular, the RAD systems, which were tested with the return air/outdoor air damper set for 100% return air, are likely to have some air leakage to the outdoors during this test.

3.4.2 Home Building Envelope Air Leakage Area

The building envelope air leakage variables and envelope air leakage area, as calculated from the building envelope depressurization tests, are summarized in Table 23 (page 166). The building envelope air leakage is expressed in terms of both ACH_{50} and specific leakage area (SLA). Figure 5 (page 104) is the cumulative frequency distribution of the measured building envelope air leakage. The median effective leakage area (ELA) was 104 square inches (in^2) and ranged from 56 in^2 to 261 in^2. The median 24-hour average wind speed was 5.7 miles per hour (mph) and ranged from 1.4 mph to 16 mph. The median 24-hour average indoor–outdoor temperature difference was 5.3°F, and ranged from -2.3°F to 14°F.

The median ACH_{50} was 4.8, and ranged from 2.8 to 8.4. The median SLA was 2.9, and ranged from 1.4 to 5.6. A total of 64 homes (60%) had SLA values less than 3.0, for which the California Title 24 Alternative Calculation Method (ACM) Manual (California Energy Commission 2001b) requires mechanical outdoor ventilation of 0.047 cubic feet per minute per square foot (cfm/ft^2). This requirement only applies to those builders taking credit for building a home with an SLA less than 3.0. It is unknown if any of the homes in this study were built taking a credit for an SLA less than 3.0. There was also one home with an SLA value of less than 1.5, for which California Title 24 additionally requires that the mechanical ventilation outdoor ventilation be sufficient to maintain an indoor air pressure with respect to the outdoors that is greater than -5 pascals with all continuous ventilation systems operating.

The median ACH_{50} of 4.8 in this study compares to the median of 5.2 in a study of 76 homes built in California since November 2002, and a median of 8.6 in a sample of 13 homes built before 1987 (Wilson and Bell 2003).

There were four homes that had ACH_{50} values exceeding 7.0, which represents 1.5 times the median of 4.8. Three of these four homes did not have a mechanical outdoor air ventilation system and one had an HRV system. Thus, the higher envelope leakage in three of these four homes cannot be attributed to penetrations associated with the mechanical outdoor air ventilation system.

3.4.3 Home-to-Garage Air Leakage

The results of the zone pressure measurements of the garage-to-home connection are summarized in Table 24 (page 167). The home-to-garage leakage areas (EqLA @ 10 Pa, in^2) had a median of 16 in^2 and ranged from 0 in^2 to 97 in^2. There are no guidelines for garage-to-home air leakage areas. The ratio of the home-to-garage leakage to the total leakage area of the home-to-outdoors and the garage-to-outdoors was also calculated, and is expressed as a percentage. This percentage had a median of 4.9% and ranged from 0% to 18%. Also measured was the home-to-garage pressure with the home-to-outdoor air pressure held at -50 Pa. The median home-to-garage pressure was -49 Pa and ranged from -34 Pa to -55 Pa. A total of 70 homes (65%) did not meet the American Lung Association guideline for a home-to-garage negative pressure of at least -49 Pa when the home is depressurized to -50 Pa (American Lung Association 2006).

One other garage-to-home metric that was calculated is the "coupling factor." This is calculated as the ratio of the garage-to-outdoor differential pressure to the home-to-outdoor differential pressure. A coupling factor equal to 0 indicates no garage-to-home coupling and a coupling factor of 1.0 indicates total coupling of the garage to the home. The median coupling factor was 0.03, and ranged from 0 to 0.26.

During the Pilot Study that preceded this field study we also conducted a limited number of tracer gas tests of garage air entering the home. Appendix A contains a complete copy of the Pilot Study report.

In the pilot study, the transport of garage air contaminants into the indoor air of the home was measured with a tracer gas technique during the 24-hour air contaminant measurements and during a subsequent two-week period. This technique uses a passive constant injection PFT. The tracer gas sources were placed by Field Team 1 at locations in the garage, approximately one week in advance of the tracer gas sampling, to allow for the emission rates of the sources to equilibrate. A total of two sources were placed at a central location in the garage. Since the emission rates from the PFT sources are temperature dependent, an air temperature data logger was deployed in the garage to log the air temperature at 15-minute intervals. These temperature data were then input into an equation of the emission rate as a function of time that was supplied by Brookhaven National Laboratory, the supplier of the PFT sources, to calculate the temperature corrected PFT emission rates. The PFT used for these tests, para-perfluorodimethylcyclohexane (p-PDCH), was a different PFT than that used to measure the outdoor air exchange rate of the home. The same PFT samplers that were used to measure the outdoor air exchange rate of the home were used to sample the garage-located PFT entering the home.

The percent of the garage air contaminant sources entering the home was determined from the ratio of the calculated source of garage PFT entering the home to the calculated source of garage PFT emitted into the garage. The emission rate of garage PFT entering the home was calculated from the average concentration of the PFT in the home (determined from the laboratory analysis of the indoor PFT sampler) multiplied by the outdoor airflow rate entering the home (determined from the tracer gas measurements of the outdoor air exchange rate and the indoor air volume of the home). For the emission rate of garage PFT into the garage, the temperature-corrected calculation of the garage PFT emission rates were used. This calculation assumes perfect mixing of the indoor home air and a zero concentration of the PFTs in the outdoor air.

The calculation of the percentage of garage emissions entering the home was calculated according to Equation (4):

$$E_{h/g} = (C_{i\text{-}pdch})\ \lambda_{pft}\ V\ 100 \ /\ E_{g\text{-}pdch} \qquad \text{(EQ 4)}$$

where:

$E_{h/g}$ = percentage of garage emissions entering home (%)

$C_{i\text{-}pdch}$ = concentration of PDCH garage tracer in the home indoor air (nL/m^3)

λ_{pft} = home outdoor air exchange rate determined from PFT measurement (h^{-1})

V = home indoor air volume (m^3)

$E_{g\text{-}pdch}$ = emission of PDCH garage tracer into garage (nL/h)

This calculation assumes that the concentration of PDCH tracer measured at the living room/dining room sampling location represented the average home indoor air concentration and that the PDCH sources in the garage represented the sources of other air contaminants in the garage.

For the 24-hour measurement period, the percentage of the garage sources entering the home ranged from 2.6% (1.9% duplicate) for Home P1, to 9.8% for Home P3, to 10.1% (11.9% duplicate) for Home P2. For the two-week measurement period, the percentage of the garage sources entering the home ranged from 4.0% for Home P1, to 7.2% for Home P2, to 11.3% (11.4% duplicate) for Home P3. The garage-to-home air leakage ratios were 3% for Home P1, 2% for Home P2, and 1% for Home P3, which compares to the median of 4.9% observed in this study. The home-to-garage pressure, with the home-to-outdoor air pressures held at -50 Pa, were -49.1 Pa for Home P1, -49.4 for Home P2, and -49.8 for Home P3.

Thus, a substantial amount of garage air, along with the contaminants released by sources in the garage (e.g., vehicle fuel and exhaust fumes, gasoline-powered lawn equipment, solvents, oils, paints, pesticides) enters the indoor air of the home.

3.5 Window/Door and Mechanical Systems Usage

The following fulfills the requirements results of Study Objective 1: Determine how residents use windows, doors, and mechanical ventilation devices, such as exhaust fans and central heating and air-conditioning systems.

3.5.1 Occupant Use of Windows and Doors for Ventilation

The window/door usage in square foot-hours (ft^2-hrs; the product of the opening area and the amount of time open) is reported for both the Test Day usage and Week Average usage. If a one square foot opening (i.e., a 4-inch opening of a typical double-hung window) is kept open for an entire day, then the calculated window opening is 24 ft^2-hrs. General population statistics are summarized in Table 25 (page 168). Figure 6 (page 105) is the cumulative frequency distribution of window door opening recorded during both the 24-hour air testing day and preceding one-week period.

The median Test Day usage was 46 ft^2-hrs, with a range of 0 ft^2-hrs to 2,448 ft^2-hrs. The Week Average usage had a median of 70 ft^2-hrs, with a range of 0 ft^2-hrs to 1,260 ft^2-hrs. The homes with zero window usage for both the Test Day and Week Average included multiple homes from the Summer and Winter field sessions and from both the North and South Regions. The maximum usage for both the Test Day and Week Average usage were both Summer field-session homes, with one being in the North and one in the South.

As an indicator of how well the usage during the Test Day compared to the usage during the previous week, the Test Day/Week Average usage ratio was calculated. This ratio had a median of 1.0, with a range of 0 to 7.0. The minimum of 0 was from multiple homes, which had no usage on the Test Day but did have usage during the previous week. The maximum of 7.0 was from a home in the Winter-South field session, where the Week Average usage was 22.5 ft^2-hrs and the Test Day usage was 3.2 ft^2-hrs.

The number of homes that had no window/door usage for the Test Day and for the preceding week was also reported. A total of 34 of the 108 homes (32%) of the homes did not use their windows during the 24-hour Test Day, and 16 of the 108 homes (15%) of the homes did not use their windows during the entire preceding week. Most of the homes with no window usage were homes in the winter field session. A total 29 of the 34 for the homes with no window usage during the Test Day were in the winter field session, which represents 53% of the homes in that session (N=55). All 16 of the homes with no window usage during the preceding week were in the winter field session, which represents 9.4% of the homes in that session.

As an indicator of how well the occupants logged their window/door usage on the written forms, the actual window/door usage measured with data loggers was compared with the data from the occupant written logs. Log/Logger ratio numbers less than 1 indicate that the window/door opening activity time-period was under-estimated on the written logs by the occupants. Log/Logger ratio numbers greater than 1 indicate that the Window/Door opening activity time period was over-estimated on the written logs by the occupants.

The Log/Logger ratio had a median of 1.0, with a range of 0.04 to 74. Note that an unusually large Log/Logger ratio may result when a Log value is divided by a very small

Logger value. Two homes had Log/Logger ratios that were unusually high. Home 008, with a Log/Logger ratio of 74, and Home 071, with a Log/Logger ratio of 24. Both these homes were from the Summer field session, with one being in the North and one in the South.

The usage of the garage door to the home, in hours of open time, is reported for use as an indicator of communication between the garage, a potential source area for indoor air contaminants such as automobiles, chemicals, solvents, etc., and the home. General population statistics, for both the Test Day usage, Week Average usage, and the Test Day/Week Average usage ratio are summarized in Table 25.

The median Test Day usage was 0.06 hrs, with a range of 0.003 hrs to 6.2 hrs. The median Week Average usage was 0.07 hrs, with a range of 0.004 hrs to 8.0 hrs. As an indicator of how well the usage during the Test Day compared to the usage during the previous week, the Test Day/Week Average usage ratio was calculated. The ratio had a median of 0.85, with a range of 0.01 to 6.1.

3.5.2 Measured and Owner-Estimated Window/Door Usage Comparison

For the participants in the UCB mail survey, the measured usage in the field session (i.e., occupant written logs) was compared with the homeowner's self-reported estimates of usage in the mail survey, to provide some information on the accuracy of that reporting. There were two sets of questions regarding window usage in the UCB mail survey.

Questions 10–25 asked for each season what the average number of hours was that windows or doors were open more than one inch for four home areas and three time periods. The four areas were: kitchen, bedrooms, bathrooms (including laundry room and utility rooms), and other rooms. The three periods of time were daytime (6 AM to 6 PM), evening (6 PM–11 PM), and nighttime (11 PM–6 AM). The question is problematic for us to compare to the data that were collected for actual usage, as it is unknown how many windows in the UCB mail survey data were open in each room and time period, or if the hours listed as open for windows in a time period represent separate, concurrent, or overlapping hours. For these reasons a comparison of the data in this study to Questions 10–25 has not been included.

Questions 28–31 asked for each season, how many hours out of a 24-hour day, on average, did your house have no ventilation, or low, medium, or high ventilation as defined below:

- No ventilation: All windows and doors closed.
- Low: One or two windows or doors open just a crack (up to one inch).
- Medium: Several windows or doors open at least a crack, or one or two windows open partway (at least several inches).
- High: Some windows or doors fully open, or several windows or doors open part-way, or almost all windows or doors open at least a crack.

As this question includes information on both the hours of window/door opening, and the number and extent of the opening, it is possible to calculate a range of reported window/door openings as square foot-hours, which then be compared to the actual measured usage. For this calculation, a range for the opening area in square feet for each of the Low-, Medium-, and High-usage categories described above was prepared. The opening area ranges, which were selected for the usage categories in square feet, are listed below:

- No ventilation: 0 ft^2
- Low: 0.1 ft^2 to 0.5 ft^2
- Medium: 1.0 ft^2 to 3 ft^2
- High: 5 ft^2 to 15 ft^2, or greater

A total of 33 homes in our field study were also present in the UCB mail survey. Of the 33 homes, 7 did not have usable responses on their Occupant Questionnaire. Many of the remaining 26 homes were repeat homes so a total of 48 home-inspection dates had data from the Homeowner Questionnaire that were compared to the estimated window usage ranges collected by the UCB mail survey. To do this calculation, the research team collected the hours of usage for each season-usage category from the UCB mail survey, Question 28–30, and multiplied it by the above opening area high and low ranges for the reported usage category. This gives a low and high range of usage for each UCB mail survey home-season that was compared to the measured usage in the field study for that home-season.

Q31 was not used, as there were no spring tests in the field study. As was done in the UCB mail survey analyses, the researchers deleted from these analyses any homes where the reported total usage hours exceeds 24 hours or where the reported usage hours are all blank (these are posted as 99 in the UCB database). For those homes where there is at least one non-blank entry to the usage hour questions, it was assumed that the blanks are zero. Percent comparisons and the population statistics of the measured versus estimated Window/Door usage are summarized in Tables 26 and 27 (pages 169 and 170).

The percentage of homes with zero measured usage and zero estimated usage was 15%. The percentage of homes with measured usage within the estimated usage range was 15%. The percentage of homes with measured usage higher than the high end of the range estimated usage was 52%. The percentage of homes with measured usage lower than the low end of the range estimated usage was 8.3%. Thus a total of just 30% of the home-seasonal comparisons had actual measured usage that agreed with the estimated usage reported in the UCB mail survey, with measured usage higher than the estimated usage comprising most of the disagreements

The research team also evaluated the magnitude of the window/door usage disagreements in Table 27. Homes that had actual measured usage but zero estimated usage had a median of 3.1 ft^2-hrs that ranged from 0.3 ft^2-hrs to 153 ft^2-hrs. The median ratio of the actual measured week average usage to the high end estimated usage in homes with higher actual usage than estimated usage was 3.1. The median ratio of the actual measured week average usage to the low end estimated usage in homes with lower actual usage than estimated usage was 0.04.

3.5.3 Occupant Use of Mechanical Exhaust Air Systems

The occupant use of mechanical exhaust air systems is reported in hours for the 24-hour Test Day usage. General population statistics are summarized in Table 28 (page 171). Figure 7 (page 106) is a cumulative frequency plot of the usage of the mechanical exhaust systems.

The median Test Day usage was 0 hrs for kitchen exhaust fans, 0.05 hours for bathroom exhaust fans, and 0.3 hours for other exhaust fans (i.e., clothes dryer, laundry/utility room). As an indicator of how well the usage during our Test Day compared to the usage during the previous week, the Test Day/Week Average usage ratio was calculated. The median ratio was 1.0 for kitchen and bathroom exhaust fans and 0.9 for other exhaust fans.

There was one home, 055, with an unusually high usage of Other Exhaust (i.e., dryer, laundry) of 17.1 hours. In this home, the laundry room fan was operated for 14.2 hours and the clothes dryer was operated for a total of 2.8 hours.

In the 2005 UCB mail survey on occupants' use of windows and mechanical ventilation equipment in 1,515 new homes in California (Price et al. 2007), 17% of the owners report they rarely use the bathroom exhaust fans, and 13% say they never use the fans. In this study, based upon the electronic logging of the two most used bathroom fans, 47% never used the fans during the 24-hour Test Day, and 27% never used the fans during the entire preceding week. Thus, the percentage of homes in this study reporting no usage of the bathroom exhaust fans from electronic logging of fan operation is notably higher than percentage of homes reporting no usage in the UCB mail survey.

In the 2005 UCB mail survey, 11% of the owners say they rarely use the kitchen range exhaust fan and 2% say they never use the fan. In this study, based upon the occupant written logs, 54% never used the fan during the one week preceding our 24-hour Test Day, and 78% never used the fan during the 24-hour Test Day. Thus, the percentage of homes in this study reporting no usage of the kitchen range exhaust fan from their written occupant logs is notably higher than the percentage of homes reporting no usage in the UCB mail survey.

3.5.4 Occupant Use of Mechanical Outdoor Air Systems

Three of the 17 homes with DOA systems (Home 001, Home 011, and Home 119) had the mechanical outdoor air systems disabled (i.e., outdoor air damper closed). The homeowners of Home 022, which had an HRV system, complained that the system brought in hot air in the summer and cold air in the winter, and thus they kept the system off the entire week except for 0.09 hours on Day 3. The analyses of the usage reported below excludes these four disabled systems.

The occupant use of mechanical outdoor air systems is reported in hours for the 24-hour Test Day usage. General population statistics are summarized in Table 28 for the two types of systems encountered in the field study: ducted outdoor air (DOA) systems and heat recovery ventilator systems (HRV). Figure 8 (page 107) is a cumulative frequency plot of the usage of the mechanical outdoor air systems.

The median Test Day usage was 2.5 hours for DOA systems and 24 hours for HRV systems. Note that five homes with HRV systems were operated continuously for 24 hours. As an indicator of how well the usage during the Test Day compared to the usage during the previous week, the Test Day/Week Average usage ratio was calculated. The median ratio was 1.1 and 1.0 for the DOA and HRV systems, respectively.

These data indicate that the DOA systems, which typically are operated intermittently and in conjunction with the operation of the FAU, operate for only a small portion of the day, while the HRV systems are typically operated continuously.

The low fractional on-times for the DOA systems are the result of the FAU fan control, which typically was controlled by the FAU thermostat fan switch and was always set in the "auto" position, and thus the fan only operated when the thermostat called for heating or cooling.

To ensure adequate delivery of outdoor air to the home, DOA systems should have a fan cycler, so that even if the thermostat fan switch does not operate the fan, the fan is operated for a minimum percentage of time. In addition, some of these fan cyclers have controls for a damper in the outdoor air duct so that this damper can be opened only for those times that outdoor air is desired. Typically these fan cyclers are set up to provide outdoor air one-third of each hour with an outdoor airflow rate that is three times higher than that required for continuous operation, and thus provide an average outdoor airflow rate over the hour that is equivalent to the flow rate of a continuous system.

Of the 17 homes with DOA systems only six had fan cyclers, four of which had automatic damper controls in the outdoor air duct. Of the 14 homes with operational DOA systems, only four had fan cyclers, three of which had automatic damper controls in the outdoor air duct. Measurements of the minimum percent operation time that these four fan cyclers provided (e.g., the percentage of on-time during the night when the thermostat was set back and only the fan cycler was causing the FAU fan to operate) indicated the following: one FAU fan was never turned on, one was on for 10 minutes for each 90-minute cycle (i.e., 0.11 fractional on-time), one was on for 10 minutes for each 30-minute cycle (i.e., 0.33 fractional on-time), and one FAU fan ran continuously, but the outdoor air damper opened 55 minutes for each 75-minute cycle (i.e., 0.73 fractional on-time).

ASHRAE 62.2-2004 (ASHRAE 2004a) requires that intermittently operated residential outdoor air mechanical ventilation systems operate at least 1 hour out of every 12 hours (i.e., a minimum fractional on-time of 0.083). Thus, three of the four DOA systems with fan cyclers met the ASHRAE 62.2-2004 minimum fractional on-time requirement. The 10 operational DOA systems, which did not have fan cyclers and were operated by the thermostat fan switch in the "auto" mode, do not meet the ASHRAE 62.2-2004 minimum fractional on-time requirement.

It is important to note that while the thermostat fan switch could be set to the "on" position, and thus overcome the low operational times of some of these DOA systems, this would not be a very energy efficient means of providing outdoor air to the home. The FAU fan system is a large fan designed to provide the large supply airflow rates required for heating or cooling the air in the home, and operating the FAU fan continuously would be a large and costly consumption of electricity. The flow rates of outdoor air required for ventilating homes is just a fraction (e.g., 5%–10%) of the total supply airflow rate delivered by the FAU fan. Thus, to ensure adequate and energy-efficient delivery of outdoor air to the home, DOA systems should include a fan cycler with fan cycle times and outdoor airflow rates set to provide the sufficient outdoor air ventilation.

Note that intermittently operated mechanical outdoor systems do not provide indoor air quality that is equivalent to that provided by continuous mechanical outdoor air systems. The concentrations of indoor air contaminants with indoor sources can increase substantially during the off periods of intermittent systems, especially for those systems with long cycle times (e.g., 12 hours), which may result in the occupants experiencing odors or irritation.

3.5.5 Occupant Use of Mechanical Nighttime Cooling Systems

The occupant use of mechanical nighttime cooling systems is reported in hours for the 24-hour Test Day usage. General population statistics are summarized in Table 28 for the two types of nighttime cooling systems encountered in the field study: whole house fan (WHF) systems and FAU return air damper (RAD) systems. Figure 9 (page 108) is a cumulative frequency plot of the usage of the mechanical nighttime cooling systems.

The median Test Day usage was 0.7 hours for WHF systems and 5.3 hours for RAD systems. As an indicator of how well the usage during the Test Day compared to the usage during the previous week, the Test Day/Week Average usage ratio was calculated. The median ratio was 0.7 for WHF fans and 1.0 for RAD systems.

Note that there were five homes where there was zero usage of the nighttime cooling system. These included three RAD systems in the winter field session and two WHF systems—one in the summer and one in the winter field sessions. Thus, the zero usage for four of these homes is consistent with the fact that the homes were in the winter field session where nighttime cooling would not be expected to be used.

These data indicate that the RAD systems encountered in this field study were operated for more hours each day than the WHF systems encountered.

3.5.6 Occupant Use of Forced Air Unit (FAU) Systems

The occupant use of mechanical FAU) heating/cooling systems is reported in hours for the 24-hour Test Day usage. For homes with multiple FAUs, data were summarized here for only FAU#1, which typically served the downstairs living/dining area. General population statistics are summarized in Table 28. Figure 10 (page 109) is a cumulative frequency plot of the FAU systems' usage.

The median Test Day usage for FAUs was 1.1 hours. A total of 32% of the homes had zero FAU usage during the 24-hour Test Day and 11% had zero usage during the preceding week. As an indicator of how well the usage during the Test Day compared to the usage during the previous week, the Test Day/Week Average usage ratio was calculated. The median ratio was 0.9.

These data indicate that the FAU systems encountered in this field study were operated for relatively few hours each day.

3.6 Outdoor Air Ventilation Measurements

This section fulfills the ventilation requirements, stated in Study Objective 2, Measure and characterize IAQ, ventilation, and the potential sources of indoor air contaminants.

3.6.1 Mechanically Supplied Outdoor Airflow Rates

The mechanically provided outdoor airflow rates for DOA and HRV systems are reported for the systems on the Test Day in units of air changes per hour (ach) and cubic feet per minute (cfm), along with the percent operation time. General population statistics and comparison to the ASHRAE 62.2-2004 requirement (ASHRAE 2004a) and the California Title 24 Alternative Calculation Method (ACM)-2001 code requirement (California Energy Commission 2001b) are summarized in Table 29 (page 172). The analyses of the outdoor airflow rates reported below excludes the four disabled mechanical outdoor air systems.

The ASHRAE 62.2-2004 requirement for mechanically provided outdoor air ventilation is calculated according to Equation 5 as follows:

$$Q_r = (0.01\ cfm/ft^2)\ A_{floor}\ ) + 7.5\ cfm\ (N_{br} + 1) \qquad (EQ\ 5)$$

where:

Q_r = required continuous mechanical outdoor airflow rate (cfm)

A_{floor} = floor area (ft^2)

N_{br} = number of bedrooms

The California Title 24 ACM-2001 code requirement for mechanically provided outdoor air ventilation is calculated according to Equation 6 as:

$$Q_r = (0.047\ cfm/ft^2)\ A_{floor} \qquad (EQ\ 6)$$

For the 14 operational DOA systems, the median 24-hour average outdoor airflow rate, in units of ach, was 0.01 ach with a minimum of 0.002 ach and a maximum of 0.08 ach. The median 24-hour average percent operation time was 10%, with a minimum of 0.6% and a maximum of 74%. The median outdoor airflow rate when the system was operational was 38 cfm, with a minimum of 8.8 cfm and a maximum of 355 cfm.

A total of 64% of DOA systems had outdoor airflow rates that failed to meet the ASHRAE 62.2-2004 guideline, and 86% failed to meet the California Building Code (CBC) 2001 requirements. Note that this comparison was made using the outdoor airflow rate that was measured when the system was operating, and assuming the system was operated continuously and not with the actual time averaged outdoor airflow rates corrected for ventilation effectiveness, as prescribed by ASHRAE 62.2-2004.

The very low outdoor air exchange rates for the DOA systems were a result of the combination of low outdoor airflow rates and low fractional on-times.

The low outdoor airflow rates were the result of the connection location of the outdoor air duct, which typically has a diameter of five or six inches. The most common connection of the outdoor air duct is to a sheet metal box just above the hallway return air inlet grille, which contains the air filter. As this air filter is typically low efficiency and has a low pressure drop, there is little negative air pressure at the outdoor air intake location to draw in outdoor air. The few systems that had the outdoor air connection located further downstream of the return air ducting (e.g., just before or at the fan box) had much higher airflow rates.

The low fractional on-times are the result of the FAU fan control, which typically was controlled by the FAU thermostat fan switch and was always set in the “auto” position, and thus the fan only operated when the thermostat called for heating or cooling. As was previously discussed in Section 3.5.4, "Occupant Use of Mechanical Outdoor Air Systems," only 4 of the 14 operational DOA systems had fan cyclers, which could be set up to ensure that the homes received adequate delivery of outdoor air.

ASHRAE 62.2-2004 (ASHRAE 2004a) requires that intermittently operated residential outdoor air mechanical ventilation systems operate at least 1 hour out of every 12 hours. The outdoor air ventilation rate for intermittently operated systems, Q_f must be increased according to Equation 7 by a factor equal to one divided by the product of the fractional on-time and the ventilation effectiveness:

$$Q_f = Q_r / (\varepsilon \times f) \qquad \text{(EQ 7)}$$

where:

Q_f = required intermittent mechanical outdoor airflow rate (cfm)

Q_r = required continuous outdoor airflow rate – see Equation 5 (cfm)

ε = ventilation effectiveness factor for intermittent ventilation

f = fractional on-time of intermittent ventilation system

The ventilation effectiveness is determined by the fractional on-time, *f*, according to the following ranges of fractional on-times:

- 0.33 ($f < 0.35$)
- 0.50 ($0.35 \leq f < 0.60$)
- 0.75 ($0.60 \leq f < 0.80$)
- 1.0 ($f \geq 0.80$)

In addition, if the system runs at least once every three hours then the ventilation effectiveness can be assumed to be 1.0.

The fan cycler in Home 021 operated the fan 10 minutes out of every 30 minutes, which is a fractional on-time of 0.33. The ventilation effectiveness for this fractional on-time is 0.33. Thus, the required increase in the outdoor airflow rate is one divided by the product of the fractional on-time of 0.33 and the ventilation effectiveness of 0.33, or an increase of 9.2 times the requirement for a continuously operated ventilation system. The ASHRAE 62.2-2004 requirement for this house, based on the square footage of the home and the number of bedrooms, is 57 cfm of outdoor air delivered continuously, or based upon the fractional on-time of the fan controller, 57 cfm times 9.2, or 524 cfm. The flowrate of outdoor air measured in this system was just 44 cfm, which is less than the continuous flow rate requirement and just 8% of the intermittent flow rate requirement.

The fan cycler in Home 099 operated the outdoor air damper 55 minutes out of every 75 minutes, which is a fractional on-time of 0.73. For some reason the FAU ran continuously in this home even though the thermostat fan switch was set for "auto." The ventilation effectiveness for this fractional on-time is 0.75. Thus, the required increase in the outdoor airflow rate is one divided by the product of the fractional on-time of 0.73 and the ventilation effectiveness of 0.75, or an increase of 1.8 times the requirement for a continuously operated ventilation system. The ASHRAE 62.2-2004 requirement for this house, based on the square footage of the home and the number of bedrooms, is 79 cfm of outdoor air delivered continuously, or based upon the fractional on-time of the fan controller, 79 cfm times 1.8, or 144 cfm. The flowrate of outdoor air measured in this system was just 10 cfm, which is less than the continuous flow rate requirement and just 7% of the intermittent flow rate requirement.

The fan cycler in Home 118 operated the fan 10 minutes out of every 90 minutes, which is a fractional on-time of 0.11. The ventilation effectiveness for this fractional on-time is 0.33. Thus the required increase in the outdoor airflow rate is one divided by the product of the fractional on-time of 0.11 and the ventilation effectiveness of 0.33, or an increase of 27.5 times the requirement for a continuously operated ventilation system. The ASHRAE 62.2-2004 requirement for this house, based on the square footage of the home and the number of bedrooms, is 38 cfm of outdoor air delivered continuously, or based upon the fractional on-time of the fan controller, 38 cfm times 27.5, or 1,047 cfm. The flowrate of outdoor air measured in this system was just 31 cfm, which is less than the continuous flow rate requirement and just 3% of the intermittent flow rate requirement.

The fan cycler in Home 102 did not operate the fan at all, The thermostat did operate the fan for 1.63 hours, however ASHRAE 62.2-2004 does not allow for intermittent operation of a mechanical outdoor air system with a thermostat and without a fan cycler because this will not ensure adequate outdoor air delivery to the home during mild weather periods when the thermostat may not turn on the FAU fan. Similarly the 10 other homes with operational DOA systems that did not have fan cyclers do not meet the ASHRAE 62.2-2004 requirements for intermittent operation of a mechanical outdoor air system.

Note that intermittent mechanical outdoor air systems, such as DOA systems, cannot perform equivalently to continuous systems such as HRV systems with respect to controlling the short-term exposures to indoor air contaminants, especially if the cycle times are long (e.g., greater than two hours). During extended outdoor air ventilation off-times, intermittent ventilation systems allow for air contaminants with indoor sources to increase substantially as compared to the increases that would occur with a continuous ventilation system. For some indoor air contaminants, such as those that cause irritation and/or odor, the effects are initiated by the immediate exposure to the indoor concentration rather than the exposure to a concentration over a period of time.

In addition, the increased outdoor air ventilation as required by ASHRAE 62.2-2004 for intermittent ventilation systems does not always provide equivalent long-term average indoor concentrations, especially for systems with long cycle times (e.g., 12 hours). The long-term average concentrations for air contaminants with indoor sources can be substantially higher in homes with intermittent ventilation systems, which is important for health effects such as cancer and cardiovascular disease.

To examine the equivalence of continuous and intermittent ventilation, a constant emission indoor air contaminant source of 1,000 μg/h was modeled in a home ventilated according to ASHRAE 62.2-2004 ventilation rates. A well-mixed single-zone computer model was used to simulate the indoor air contaminant concentrations for a 4-bedroom home with a 1,500 ft^2 floor area, 8-ft ceiling height, and a 12,000-cubic foot (ft^3) indoor air volume. The simulation used one-minute time steps for a 24-hour period with the initial concentration set to equal the concentration at the end of the 24-hour simulation and assumed a zero air contaminant concentration in the outdoor air. The outdoor air ventilation rate for a continuous ventilation system as prescribed by ASHRAE 62.2-2004 is 52 cfm for this home. In addition, the research team included an infiltration rate of outdoor air into the home equal to the ASHRAE 62.2.-2004 infiltration default credit of 2 cfm/100 ft^2.

For the intermittent ventilation system the research team used a cycle time of 12 hours and a fractional on-time of 0.10, which according to ASHRAE 62.2-2004 has a ventilation effectiveness factor of 0.33.

Figure 11 (page 110) is a plot of the modeled indoor air contaminated concentrations for continuous and intermittent ventilation systems. The average 24-hour indoor air contaminant concentration was 9.3 μg/m^3 for the intermittent ventilation system, which is 29% higher than the 7.2 μg/m^3 average concentration for the continuous system. In addition, the maximum indoor air contaminant concentration was 15.9 μg/m^3 for the intermittent ventilation system, which is 220% higher than the 7.2 μg/m^3 maximum concentration for the continuous system.

For the analyses of the HRV systems, Home 022 was excluded because the homeowner had turned the system off for the 24-hour Test Day as well as for all but 0.9 hours of the preceding week. For the 8 operational HRV systems, the median 24-hour average outdoor airflow rate, was 0.30 ach with a minimum of 0.12 ach and a maximum of 0.47 ach. The median 24-hour average percent operation time was 100%, with a minimum of 32% and a maximum of 100%. The median outdoor airflow rate when the system was operational, in units of cfm, was 128 cfm, with a minimum of 66 cfm and a maximum of 159 cfm.

None of the HRV systems failed to meet the ASHRAE 62.2-2004 guideline, and 22% failed to meet the CBC 2001 requirements. The two homes that failed to meet the CBC 2001 requirement were the result of low outdoor airflow rates and not low operating times.

These results show that, as encountered in this field study, HRV systems are a more effective outdoor air supply strategy than the DOA systems.

3.6.2 Tracer Gas Measurements of Home Outdoor Air Exchange Rates

The air changes per hour (ach) in the homes are reported over the 24-hour Test Day and the two-week measurement period. General population statistics are summarized in Table 30 (page 173). Figure 12 (page 111) is a cumulative frequency plot of the 24-hour outdoor air exchange rate measurements.

The median 24-hour measurement was 0.26 ach, with a range of 0.09 ach to 5.3 ach. The median two-week measurement was 0.24 ach, with a range of 0.11 ach to 2.3 ach. As an indicator of how well the 24- hour Test Day ach compared with the two-week period ach, the absolute and relative difference between the 24-hour versus two-week period measurements was calculated for the all homes with both measurements (i.e., not just those homes in the All Home sample frame). The median absolute difference was 0.07 ach, with a range of 0.001 to 5.1. The median relative standard deviation was 0.19, with a range of 0.01 to 1.1 (Table 30, page 173).

The 24-hour Test Day measurements were compared to the CBC code requirement of 0.35 ach and then the outdoor air exchange rate/CBC 2001 minimum code requirement ratio for homes that were below the code requirement was calculated. There were 72 homes (67%) with outdoor air exchange rates below the minimum code requirement of 0.35 ach. General population statistics for these homes are summarized in Table 31 (page 174). The median ratio was 0.58, with a range of 0.25 to 1.00.

There were eight homes with outdoor air exchange rates exceeding 1.25 ach, which is 4.8 times the median of 0.26 ach. Of these eight homes, seven were homes in the Summer Field session, with six of these homes having relatively high window usage of between 421 and 1306 ft^2-hrs. In addition, four of these eight homes had mechanical outdoor air ventilation systems, including two HRV, one WHF, and one DOA.

On the other end of the spectrum there were eight homes with outdoor air exchange rates less than 0.12 ach, which is less than half of the median of 0.26 ach. Of these eight homes, seven were homes in the winter field session, with six of these homes having zero window usage. In addition, four of these eight homes had operating mechanical outdoor air ventilation systems, all of which were DOA systems.

There were two homes where the outdoor air exchange rate was substantially less than the measured mechanical outdoor air ventilation rates.

The 24-hour average mechanical outdoor air exchange rate for Home 034 was 3.7 ach, whereas the PFT 24-hour measured outdoor air exchange rate was 0.59 ach. The FAU did not operate at all during this period and the whole house exhaust fan operated for 11.3 hours. There was a lot of window opening, 457 ft^2-hrs, of which 72% was located on the second floor, where the inlet to the whole house exhaust fan was located. As the PFT air sampler was on the first floor and the whole-house exhaust fan was exhausting air on the second floor with most of the open windows, the airflow into the exhaust fan was mostly from the second floor open windows creating a two-zone situation, with lower ventilation rates on the first floor where the PFT sampler was located.

The 24-hour average mechanical outdoor air exchange rate for Home 044 was 2.2 ach, whereas the PFT 24-hour measured outdoor air exchange rate was 0.86 ach. The FAU did not operate at all during this period and the whole-house exhaust fan operated for 4.8 hours. There was also a window fan blowing outdoor air into the second floor for 18.5 hrs. There was a lot of window opening, 301 ft^2-hrs, of which 34% was located on the second floor, where the inlet to the whole house exhaust fan was located. As the PFT air sampler was on the first floor and the whole house exhaust fan was exhausting air on the second floor with most of the open windows, the airflow into the exhaust fan was mostly from the second floor open windows, creating a two-zone situation, with lower ventilation rates on the first floor where the PFT sampler was located.

It is important to note that the ventilation inefficiencies caused by poor mixing of the indoor air, such as in these two homes, has the most impact in homes where the outdoor air exchange rates are high (e.g., greater than 2 ach); in homes with lower outdoor air exchange rates (e.g., less than 0.5 ach) there is much less of an impact. This is because in homes with low outdoor air exchange rates, the air has a longer residence time in the home, which allows for more mixing of the indoor air to occur from mechanically and thermally induced airflows.

3.7 Indoor Air Quality Measurements

This section fulfills the indoor air quality requirements stated in Study Objective 2, Measure and characterize indoor air quality (IAQ) ventilation, and the potential sources of indoor air contaminants.

3.7.1 Integrated Time Averaged IAQ Measurements (24-hour)

3.7.1.1 Volatile Organic Compounds Concentrations

Table 32 (page 175) contains the analytical method mass detection limit, MDL mass, the typical air sample method detection limit concentration, MDL concentration, the indoor air contaminant concentration guidelines, the ratio of the MDL concentration to the indoor air contaminant concentration guidelines, and the percentage of samples with concentrations above the MDL concentration for volatile organic compounds.

The primary selection of an indoor air contaminant concentration guideline for VOCs for this project was the California Air Resources Board Indoor Air Pollution in California, Table 4.1 ARB Indoor Air Quality Guidelines, July 2005 (California Air Resources Board 2005). The second basis for selection, for those compounds without ARB indoor air guidelines, is the California Office of Environmental Health Hazard Assessment Chronic RELs (OEHHA 2003). The final basis of selection, for those compounds with neither ARB indoor guidelines or OEHHA Chronic RELs, is 2.5% of the occupational standard. This recommendation is based upon the different exposure periods (40-hour week for an industrial worker versus 168-hour per week for a full-time occupant) and to provide a safety factor of ten for more sensitive populations (Nielsen 1997).

The ratio of the MDL concentration to the indoor air contaminant concentration guidelines ranged from 4E-5 (0.00004) for 2-butoxyethanol and n-hexane to 2E-2 (0.02) for naphthalene.

The percentage of homes with indoor concentrations exceeding the MDL concentration ranged from 0% for caprolactam to 100% for phenol and toluene. The percentage of outdoor air samples with concentrations exceeding the MDL concentration ranged from 0% for ethylene glycol, 1-methyl-2-pyrrolidinone, trichloromethane, and vinyl acetate to 98% for phenol.

The indoor concentrations of VOCs are summarized in Table 33 (page 176). Figures 13–25 (pages 112–124) are cumulative frequency plots of the indoor and outdoor concentrations of the 15 VOCs that have Chronic RELs (OEHHA 2003). The median indoor concentrations ranged from 0.1 $\mu g/m^3$ for caprolactam and 1,4-dichlorobenzene to 11 $\mu g/m^3$ for d-limonene and alpha-pinene. The maximum indoor concentrations ranged from 0.1 $\mu g/m^3$ for caprolactam to 219 $\mu g/m^3$ for 1,4- dichlorobenzene.

The outdoor concentrations of VOCs are summarized in Table 34 (page 177). The median outdoor concentrations ranged from 0.1 $\mu g/m^3$ for 2-butoxyethanol, caprolactam, 1,4-dichlorobenzene, naphthalene, alpha-pinene, and styrene to 1.2 $\mu g/m^3$ for toluene. The maximum outdoor concentrations ranged from 0.2 $\mu g/m^3$ for 1-methyl-2-pyrroldinone, naphthalene, trichloromethane, and vinyl acetate, to 6.3 $\mu g/m^3$ for toluene.

The maximum indoor concentrations of VOCs are compared to the indoor air contaminant guidelines in Table 35 (page 178). None of the indoor concentrations of the 20 VOCs exceeded the indoor air contaminant guidelines. The ratio of the maximum indoor concentration and indoor air contaminant guideline ranged from less than 0.0001 for caprolactam to 0.646 for tetrachloroethene. There were several homes where the indoor concentrations were substantially higher than the median (i.e., 25 times or more higher).

Homes 097 and 022 both had indoor concentrations of 1,4-dichlorobenzene that were between 1,600 and 2,200 times higher than the median of 0.1 μg/m^3 (i.e., 161 μg/m^3 in Home 022 and 219 μg/m^3 in Home 097). The outdoor air exchange rates in these two homes were not unusually low—0.64 ach in Home 097 and 0.41 ach in Home 022. Thus, an indoor source of 1,4-dichlorobenzene appears to be the primary cause of these elevated concentrations. An examination of the potential indoor sources in these two homes indicates that mothballs, a known source of this chemical, is the likely source. There were a total of seven homes where the homeowners reported the use of mothballs, including the two homes cited above. Two of the other five homes where use of mothballs was reported also had indoor concentrations that were relatively high in comparison to the median; Home 094 with concentrations 760 times higher (i.e., 75.6 μg/m^3) and Home 071 with concentrations 335 times higher (i.e., 33.5 μg/m^3).

Home 112 had indoor concentrations of naphthalene that was 25 times higher than the median of 0.2 μg/m^3. The outdoor air exchange rate in this home was also not unusually low, 0.31 ach. Thus, an indoor source of naphthalene appears to be the primary cause of the elevated concentration. An examination of the potential indoor sources in this home indicates that mothballs, a known source of this chemical, is also the likely source. In the United States naphthalene is no longer used to make mothballs; instead 1,4-dichlorobenzene is used. However, people still have these mothballs stored at home or bring them into the United States from abroad.

Home 074 had indoor concentrations of styrene that were 75 times higher than the median of 0.9 μg/m^3. The outdoor air exchange rate in this home was relatively low, 0.17 ach, which contributed to the elevated indoor concentration. An examination of the potential indoor sources in this home did not reveal any indoor sources. While a potential indoor source of styrene is polystyrene, no unusual amount of this material was observed in the home. It is possible that polystyrene materials may be used in construction of this home that are not visible, such as structural insulated panels (SIPs), which often contain polystyrene,

Home 075 had indoor concentrations of tetrachloroethene that was 15 times higher than the median of 0.2 μg/m^3. The outdoor air exchange rate in this home was relatively low, 0.25 ach, which contributed to the elevated indoor concentration. An examination of the potential indoor sources in this home indicates that dry cleaned clothes or drapes, a known source of this chemical, is the likely source. The homeowner reported that clothes or drapes had been dry-cleaned within the last week.

Home 120 had indoor concentrations of trichloromethane (chloroform) that was 60 times higher than the median of 0.2 μg/m^3. The outdoor air exchange rate in this home was relatively low, 0.12 ach, which contributed to the elevated indoor concentration. An examination of the potential indoor sources in this home indicates that use of chlorinated water, a known source of this chemical, is the likely source. The homeowner reported showering or bathing, warming/boiling water, and use of the clothes washer during the 24-hour air sampling Test Day.

Unlike the other homes in this study, which at most had one or two volatile organic compounds with concentrations substantially higher than the median, Home 108 had five compounds with elevated concentrations; benzene at 11 times the median, n-hexane at 26 times the median, toluene at 12 times the median, m, p-xylene at 14 times the median, and 0-xylene at 17 times the median. The outdoor air exchange rate in this home was relatively low, 0.24 ach, which contributed to the elevated indoor concentrations. Potential sources of these compounds include paints, caulking, and solvents. The homeowner reported painting and caulking of the exterior of the front door and the purchase of two new leather recliners within the last six months, and spot cleaning or dry cleaning of the carpet within the last two months.

3.7.1.2 Formaldehyde and Acetaldehyde Concentrations

Table 32 (page 175) contains the analytical method mass detection limit (MDL mass), the typical air sample method detection limit concentration (MDL concentration), the indoor air contaminant concentration guidelines, the ratio of the MDL concentration to the indoor air contaminant concentration guidelines, and the percentage of samples with concentrations above the MDL concentration for formaldehyde and acetaldehyde.

The selections of indoor air contaminant concentration guidelines for formaldehyde and acetaldehyde for this project were the California Air Resources Board, Indoor Air Pollution in California, Table 4.1 ARB Indoor Air Quality Guidelines, July 2005 (California Air Resources Board 2005) and the California Office of Environmental Health Hazard Assessment Chronic RELs (OEHHA 2003) and Acute RELs (OEHHA 2000). For formaldehyde, the OEHHA Chronic REL (OEHHA 2003) of 3 $\mu g/m^3$ and the OEHHA Acute REL (OEHHA 2000) of 94 $\mu g/m^3$ was included, in addition to the ARB Indoor Air Guideline of 33 $\mu g/m^3$. For acetaldehyde, the OEHHA Chronic REL of 9 $\mu g/m^3$ (OEHHA 2003) was included.

The ratio of the MDL concentration to the indoor air contaminant concentration guidelines ranged from 9E-3 (0.009) for formaldehyde (ARB Indoor Air Guideline of 33 $\mu g/m^3$) to 3E-2 (0.03) for acetaldehyde (OEHHA Chronic REL of 9 $\mu g/m^3$).

The percentage of homes with indoor concentrations exceeding the MDL concentration was 100% for both formaldehyde and acetaldehyde. The percentage of outdoor air samples with concentrations exceeding the MDL concentration was 97% for both formaldehyde and acetaldehyde.

The indoor concentrations of formaldehyde and acetaldehyde are compared to the indoor air contaminant guidelines in Table 36 (page 179). Figures 26 and 27 (pages 125 and 126) are cumulative frequency plots of the indoor and outdoor concentrations of acetaldehyde and formaldehyde.

The median indoor concentration of formaldehyde was 36 μg/m^3, with a range of 4.8 μg/m^3 to 136 μg/m^3.

For formaldehyde, all of the homes exceeded the Chronic REL of 3 μg/m^3, 59% exceeded the ARB Indoor Air Guideline of 33 μg/m^3, and a total of 6.7% exceeded the OEHHA Acute REL of 94 μg/m^3.

For those homes exceeding the indoor formaldehyde guidelines, the ratio of the indoor concentrations to the indoor air contaminant guidelines were also calculated. The median ratio was 12, with a range of 1.6 to 45 for the Chronic REL of 3 μg/m^3; 1.5, with a range of 1.0 to 4.1 for the ARB indoor air guideline of 33 μg/m^3; and 1.2, with a range of 1.0 to 1.4 for the OEHHA Acute REL of 94 μg/m^3.

The median indoor concentration of acetaldehyde was 20 μg/m^3, with a range of 1.9 μg/m^3 to 102 μg/m^3. The median indoor concentration of acetaldehyde was 20 μg/m^3, with a range of 1.9 μg/m^3 to 102 μg/m^3.

For acetaldehyde a total of 82% of the 105 homes exceeded the OEHHA Chronic REL of 9 μg/m^3. For homes exceeding the indoor acetaldehyde guidelines, the ratio of the indoor concentrations to the indoor air contaminant guidelines was also calculated. The median ratio was 2.5, with a range of 1.2 to 11.

Figure 28 (page 127) compares the indoor formaldehyde concentrations and the outdoor air exchange rates in 84 homes without mechanical outdoor air ventilation systems and in 38 homes with working mechanical outdoor air ventilation systems (i.e., 17 pure DOA, 6 pure HRV, and 15 other and mixed mechanical outdoor air systems). Also included in Figure 28 are the median ASHRAE 62.2-2004 (ASHRAE 2004a) and California Title 24 ACM (California Energy Commission 2001b) recommendations for mechanical outdoor air ventilation as calculated for the specific homes in this study. The ASHRAE 62.2-2004 median calculated rate was 0.15 ach, while the California Title 24 ACM median calculated rate was 0.30 ach.

Note that ASHRAE 62.2-2004 assumes that natural infiltration will add to the mechanically supplied outdoor air exchange rate a total of 2 cfm/100 ft^2, or 0.15 ach, assuming an 8 ft ceiling height. However, if the indoor-outdoor temperature difference and wind speed are low, the natural infiltration rates can be much less than 0.15 ach. For a two-story home with a building envelope leakage equal to the median of the sample of homes in this study (i.e., ACH_{50} of 4.8 or SLA of 2.9), the natural infiltration rate for an indoor-outdoor temperature difference of 2˚F and a wind speed of 2 mph, is just 0.08 ach. This is calculated according to the ASHRAE Basic Model (ASHRAE 2005). Furthermore, if the mechanical outdoor air ventilation system is not a balanced system, such as the DOA systems in this study, then the natural infiltration rates can be substantially muted when the system is operating. For those systems equipped with fan cyclers set to operate the system for 33% operation time, the added natural infiltration is reduced from 0.08 ach to 0.06 ach, as calculated according to the ASHRAE-recommended calculation for combining infiltration and mechanical ventilation outdoor rates (ASHRAE 2005). If an unbalanced system is set up to run at a low continuous rate, then the added natural infiltration rate can be reduced from 0.08 ach to less than 0.01 ach.

Figure 28 also includes the California Air Resources Board recommended maximum indoor 8-hour formaldehyde exposure guideline of 33 $\mu g/m^3$ (California Air Resources Board 2005). This guideline was developed to protect sensitive subgroups of the population to non-cancer irritant effects. In 2004, the World Health Organization designated formaldehyde as a known human carcinogen (IARC 2004).

As can be seen in Figure 28, there are few homes with outdoor air exchange rates of at least 0.5 ach that had indoor concentrations of formaldehyde above the recommended maximum indoor concentration of 33 $\mu g/m^3$; just 5 of 122 homes, or 4%, of the homes. For homes with outdoor air exchange rates of at least 0.30 ach (i.e., the median mechanical rate recommended by California Title 24 ACM for the homes in this study), a total of 14 of 38 homes, or 37%, had indoor concentrations of formaldehyde above 33 $\mu g/m^3$. For homes with outdoor air exchange rates of at least 0.15 ach (i.e., the median mechanical rate recommended by ASHRAE 62.2-2004 for the homes in this study), a total of 32 of 57 homes, or 56%, had indoor concentrations of formaldehyde above 33 $\mu g/m^3$.

If we look separately at the number of homes with indoor formaldehyde concentrations exceeding the 33 $\mu g/m^3$ guideline, we find that 55% (46 of 84) of homes without mechanical outdoor air ventilation systems, 100% (i.e., 17 of 17) of homes with DOA systems, and 50% (i.e., 3 of 6) homes with HRV systems exceeded this guideline. Note that one of the three HRV system homes with elevated indoor formaldehyde concentrations was only operated 32% of the time via a manual switch by the homeowner.

3.7.1.3 Nitrogen Dioxide

Table 37 (page 180) contains the analytical method mass detection limit (MDL mass), the typical air sample method detection limit concentration (MDL concentration), the indoor air contaminant concentration guidelines, the ratio of the MDL concentration to the indoor air contaminant concentration guidelines, and the percentage of homes with indoor and outdoor concentrations above the MDL concentration.

The California Air Resources Board 24-hour guideline of 150 $\mu g/m^3$ (California Air Resources Board 2005) was selected as an indoor air contaminant concentration guideline for nitrogen dioxide.

The MDL concentration of 5.7 μg/m³ was determined by dividing the MDL mass of 0.8 μg with the typical air sample volume (i.e., 140 L). The ratio of the MDL concentration to the indoor air contaminant concentration guideline is 0.04.

The percentage of the homes (i.e., Winter-North homes only) with indoor concentrations exceeding the MDL concentration was 48%. The percentage of the outdoor air samples with concentrations exceeding the MDL concentration was 9%.

The indoor and outdoor concentrations of nitrogen dioxide are summarized in Table 38 (page 181). The median indoor concentration was 3.1 μg/m³, with a range of 2.6 μg/m³ to 50 μg/m³. The median outdoor concentration was 2.9 μg/m³, with a range of 2.7 μg/m³ to 14 μg/m³.

None of the indoor or outdoor nitrogen dioxide concentrations exceeded the 150 μg/m³ guideline.

In addition, none of the homes exceeded the California Air Resources Board annual ambient air quality standard of 56 μg/m³ for outdoor air. (California Air Resources Board 2007a).

3.7.1.4 Particulate Matter ($PM_{2.5}$)

Table 37 (page 180) contains the analytical method mass detection limit (MDL mass), the typical air sample method detection limit concentration (MDL concentration), the indoor air contaminant concentration guidelines, the ratio of the MDL concentration to the indoor air contaminant concentration guidelines, and the percentage of homes with indoor and outdoor concentrations above the MDL concentration.

The California Air Resources Board 24-hour guideline of 65 μg/m³ was selected as the indoor air contaminant concentration guideline for $PM_{2.5}$ (California Air Resources Board 2005).

The MDL concentration of 1.8 μg/m³ was determined by dividing the MDL mass of 5 μg with the typical air sample volume (i.e., 2.8 m³). The ratio of the MDL concentration to the indoor air contaminant concentration guideline is 0.03.

The percentage of the homes (i.e., Winter-North homes only) with indoor concentrations exceeding the MDL concentration was 100%. The percentage of the outdoor air samples with concentrations exceeding the MDL concentration was 100%.

The indoor concentrations of $PM_{2.5}$ are summarized in Table 38 (page 181). The median indoor concentration was 11 μg/m³, with a range of 3.8 μg/m³ to 36 μg/m³. The median outdoor concentration was 8.7 μg/m³, with a range of 4.3 μg/m³ to 12 μg/m³.

None of the indoor or outdoor concentrations of $PM_{2.5}$ particulate matter exceeded the 65 μg/m³ ARB 24-hour average indoor air guideline.

The EPA recently established a lower $PM_{2.5}$ 24-hour requirement of 35 μg/m³ (EPA 2007) for outdoor air. Only one of the homes exceeded this concentration—Home 116, which had an indoor concentration of 36 μg/m³. The outdoor concentration was 8.9 μg/m³, which indicates a substantial indoor source of $PM_{2.5}$ particulate matter in this home.

The Occupant Source Activity Log was examined to see if there were any activities that might have contributed to the elevated indoor concentrations of $PM_{2.5}$. The only substantial activity was 180 minutes of baking. While there was a fireplace and candles in the living room where the air sampler was located, the occupant did not report any usage of the fireplace or any candle burning. The occupancy of this home was relatively high and included two adults, two children under 18 years old, two dogs, two hamsters, and one goldfish. Contributing to the elevated indoor concentration of $PM_{2.5}$ is the relatively low outdoor air exchange rate of 0.22 ach.

3.7.2 Real-Time IAQ Measurements

3.7.2.1 Carbon Monoxide (CO)

Table 37 (page 180) contains the method detection limit concentration, the indoor air contaminant concentration guidelines, the ratio of the MDL concentration to the indoor air contaminant concentration guidelines, and the percentage of homes with indoor and outdoor concentrations above the MDL concentration.

For indoor air contaminant concentration guidelines for carbon monoxide, the California Air Resources Board 8-hour guideline of 9 ppm and the 1-hour guideline of 20 ppm (California Air Resources Board 2005) was selected. There is no 24-hour exposure guideline for carbon monoxide.

The ratio of the MDL concentration to the indoor air contaminant concentration guideline is 0.09.

The percentage of the homes with indoor concentrations exceeding the MDL concentration was 100%. The percentage of the outdoor air samples with concentrations exceeding the MDL concentration was 100%.

The indoor concentrations of carbon monoxide are summarized in Table 38 (page 181). The median maximum 8-hour average indoor concentration was 1.1 ppm, with a range of 0.4 ppm to 3.7 ppm. The median maximum 8-hour average outdoor concentration was 1.9 ppm, with a range of 0.4 ppm to 4.4 ppm.

The median maximum 1-hour average indoor concentration was 1.6 ppm, with a range of 0.4 ppm to 6.8 ppm. The median maximum 8-hour average outdoor concentration was 2.4 ppm, with a range of 0.4 ppm to 4.9 ppm.

None of the indoor or outdoor concentrations of carbon monoxide exceeded either the 9 ppm 8-hour guideline or the 20 ppm 1-hour guideline.

3.7.2.2 Carbon Dioxide (CO_2)

The indoor and outdoor concentrations of carbon dioxide are summarized in Table 39 (page 182). The median indoor concentration was 564 ppm, with a range of 334 ppm to 1,108 ppm. The median outdoor concentration was 323 ppm, with a range of 258 ppm to 369 ppm.

Note that measurements of the outdoor concentration of carbon dioxide less than 375 ppm are indicative of a measurement error, as the atmospheric concentration of carbon dioxide measured at the Mauna Loa Observatory in Hawaii in 2006–2007 ranged from 375–385 ppm. These measurements are not influenced by urban sources of atmospheric carbon dioxide, such as vehicle and industrial combustion exhaust fumes, and thus represent the minimum concentration of carbon dioxide in outdoor air.

The carbon dioxide sensors used, TSI IAQ-Calcs, are non-dispersive infrared spectrophotometers and were calibrated with certified calibration gasses before and after each 24-hour sampling period. It was first thought that changes in the outdoor air temperature might be causing this error. To test this hypothesis, the research team calibrated the instrument at room air temperature and then measured the instrument's response to 1,035 ppm calibration gas with the instrument and the calibration gas at 70˚F and then at 41˚F. The response of the instrument decreased by 230 ppm (22%) at the 41˚F temperature.

A review of the minute-by-minute concentrations of outdoor carbon dioxide concentrations and the outdoor air temperature from homes with very low outdoor air 24-hour average concentrations (e.g., 260 ppm) suggest that the response of the sensor decreases with the outdoor air temperature.

The impact of relative humidity on the response of the sensor was also examined. The instrument was calibrated at room air temperature and the research team measured its response to 1,035 ppm calibration gas directly from the compressed gas cylinder to the sensor, and then with the calibration gas passed through a series of water filled bubblers and then to the sensor. The relative humidity of the calibration gas was 1.6% directly from the compressed gas cylinder and 87% after passing through the bubblers. The response of the sensor to the 1,025 ppm calibration gas decreased by 40 ppm (3.8%) at 87% relative humidity.

Thus, it appears that the major error associated with the outdoor carbon dioxide measurements is associated with outdoor air temperature changes. No attempt has been made to correct these data, nor have any data where this effect appears to be occurring been deleted.

It is not anticipated that this type of error is associated with the indoor air measurements since there are not large changes in the indoor air temperatures as there are with outdoor air temperatures.

3.7.2.3 Temperature and Relative Humidity

The indoor and outdoor air temperatures and relative humidities are summarized in Table 39 (page 182). The median indoor air temperature was 72.3°F, with a range of 62.7°F to 82.8°F. The median outdoor air temperature was 63.8°F, with a range of 44.9°F to 82.4°F. The median indoor air relative humidity was 45.2%, with a range of 19.5% to 63.5%. The median outdoor air relative humidity was 57.9%, with a range of 25.1% to 93.3%.

3.7.3 Volatile Organic Compound Concentration Study Comparisons

Table 40 (page 183) compares the concentrations of VOCs measured in this study to those measured in two other studies in new homes as summarized by Hodgson and Levin (2003). In the Hodgson and Levin paper they present the geometric mean and the maximum concentrations observed in six experimental low-emitting homes and three conventional homes built in Denver, Colorado in 1992–1993 and four manufactured homes and seven site-built homes built in the east and southeast United State in 1997–1998. The measurements of VOCs were made within the first six moths after the homes were completed. The four manufactured homes were unoccupied but furnished, and the seven site-built homes were unoccupied and unfurnished, but finished, including cabinetry and carpeting. One of the four manufactured homes had a DOA outdoor air ventilation system with a fan cycler. One of the seven site-built homes had a DOA outdoor air ventilation system with a fan cycler, and one home had an HRV system. The six experimental homes and three conventional homes were tested both during pre-occupancy period without furnishings and a post-occupancy period with furnishings. Each of six experimental homes had continuous outdoor air ventilation systems, of which three were HRVs.

The outdoor air exchange rates were lower in the new homes in this study, with a geometric mean outdoor air exchange rate of 0.31 ach and a geometric mean outdoor air exchange rate of 0.44 ach for the 20 new homes in the other studies.

There were 13 VOCs measured in this study that were all measured in the two other studies. For comparison purposes, Table 40 presents the ratio of the geometric mean concentrations observed in this study with the geometric mean concentration in the two other studies. A total of 7 of the 13 compounds had a ratio of the geometric mean concentrations between 0.5 and 2, with 8 of the 13 having ratios greater than 1.0. There were two compounds in this study with a ratio of more than 2: benzene (4.4) and trichloromethane (4.0).

There were also two compounds with a ratio of less than 0.5: alpha-pinene (0.4) and ethylene glycol (0.1).

Also included in Table 40 is a comparison of the maximum concentrations in this study and the other two studies. A total of 12 of the 13 compounds had a ratio of maximum concentrations exceeding 1.0. There were 8 compounds in this study with a ratio of more than 2: trichloromethane (24), 2-butoxyethanol (15), d-limonene (13), m, p – xylene (5.5), o-xylene (4.5), benzene (2.5), acetaldehyde (2.4), and formaldehyde (2.2).

There was also one compound with a ratio of less than 0.5: ethylene glycol (0.2).

3.7.4 Volatile Organic Compound Proposition 65 Safe Harbor Levels

Table 41 (page 184) presents the percentage of homes with indoor concentrations that exceed the California Proposition 65 Safe Harbor Levels (OEHHA 2008a). Table 41 contains the calculated indoor concentrations associated with the No Significant Risk Levels (NSRL) for carcinogens and the Maximum Allowable Dose Levels (MADL) for chemicals causing reproductive toxicity. These calculated indoor concentrations assume a continuous 24-hour exposure with a total daily inhaled air volume of 20 m^3 and 100% absorption by the respiratory system. The NSRL is the daily intake level calculated to result in one excess case of cancer in an exposed population of 100,000. The MADL is the level at which reproductive toxicity would have no observable effect, assuming exposure at 1,000 times that level.

Of the 22 volatile organic compounds measured in this study, there were eight with California Proposition 65 Safe Harbor Levels. For each of the seven VOCs with NSRLs, there were some homes that exceeded the calculated indoor NSRL concentration. The percentage of homes exceeding the calculated indoor NSRL concentration ranged from 8% for trichloromethane (chloroform) and tetrachloroethene to 93% for acetaldehyde and 100% for formaldehyde.

For the two volatile organic compounds with MADLs, benzene and toluene, there were homes that exceeded the calculated indoor MADL concentration only for benzene. The percentage of homes exceeding the calculated indoor MADL concentration for benzene was 20%.

3.8 Homeowner Source Activity Log

This section fulfills the potential sources requirements stated in Study Objective 2, Measure and characterize indoor air quality (IAQ), ventilation, and the potential sources of indoor air contaminants. Other potential sources have previously been summarized in the Home and Site Characteristic Collection Section.

The indoor source activities were reported by the occupants for the 24-hour Test Day and are summarized in Tables 42 and 43 (page 185 and 186).

The cooking and cleaning activities logged by the homeowner during the 24-hour Test Day are summarized in Table 42. The median total cooking activity time was 35 minutes, and ranged from a minimum of 0.3 minutes to a maximum of 295 minutes. The median cooking activity times with the three highest times were: baking (45 minutes), warming/boiling water soup etc. (20 minutes), and broiling (19 minutes). The median total cleaning activity time was 83 minutes, and ranged from a minimum of 1 minute to a maximum of 800 minutes. The median cleaning activity times with the three highest times were: dishwasher (68 minutes), use of clothes washer (59 minutes), and vacuuming (25 minutes).

The special, garage, and outdoor source activities logged by the homeowner during the 24-hour Test Day are summarized in Table 43. The median total special activity time was 30 minutes, and ranged from a minimum of 0.3 minutes to a maximum of 1,440 minutes. The median special activity times with the three highest times, other than "nobody at home" were: candle burning (165 minutes), gas-burning fireplace (140 minutes), and other activities that produce dust, smoke, or fumes (140 minutes). The median total garage activity time was 1,037 minutes and ranged from a minimum of 0.3 minutes to a maximum of 3,480 minutes. This maximum of 3,480 minutes reflects the storage of multiple cars in the garage. The median vehicle operated in the garage time was 2 minutes, and ranged from a minimum of 0.2 minutes to a maximum of 10 minutes. The median total outdoor activity time was 29 minutes, with a minimum of 1 minute and a maximum of 360 minutes. The median outdoor activity times with the three highest times were: painting (55 minutes), use of gasoline-powered equipment (25 minutes), and smoking outdoors (25 minutes).

3.9 Homeowner Reported IAQ Related Perceptions and Observations

This section fulfills requirements stated in Study Objective 3, Determine occupant perceptions of, and satisfaction with, the IAQ in their homes.

The homeowner self-reported perceptions and satisfaction with the IAQ in their homes are summarized in Table 44 (page 187) for the three-week recall period. In the Occupant Questionnaire there were a total of nine physical symptom questions where the occupants were asked "During the past three weeks have you experienced any of the following physical symptoms when in your home that you do not experience when you are away from the home?". A total of 30 of the 108 homeowners (28%) reported experiencing one or more of the nine physical symptoms. The three most frequently reported symptoms were nose/sinus congestion (19%), allergy symptoms (15%), and headache (13%).

This Occupant Questionnaire also included a total of seven home comfort questions where the occupants were asked "During the past week, please indicate if you have noticed a significant period when your home has experienced each of the conditions listed below." The three most frequently reported conditions were "too cold" (19%), "too hot" (15%), and "too stagnant (not enough air movement)" (12%).

In the 2005 UCB mail survey of new homes in California (Price et al. 2007), 60% of the homeowners in the summer reported at least one thermal comfort problem and 58% reported the same in the winter. Those results are notably higher than the results in this field study: 38% in the winter and 43% in the summer. The UCB mail survey also reported that thermal comfort problems were higher in the summer in the winter (i.e., 60% and 58%, respectively) than in the spring and fall swing seasons (i.e., 24% and 29%, respectively).

Also included were three questions regarding mold or mildew. "During the past week, please indicate if you have noticed, seen, or smelled mold or mildew in the following locations?". The most frequently reported location where the homeowners report mold or mildew was the bathroom, which was reported by 13% of the occupants. Other locations were also reported by between 0.9% and 2.8% of the occupants.

In the 2005 UCB mail survey (Price et al. 2007), homeowners were asked if they "noticed, saw or smelled mold or mildew" in the bathroom during the different seasons. The percentage of homeowners reporting mold or mildew in the bathroom ranged from 4% in the spring to 7% in the winter. The percentage of homeowners reporting mold in other locations (i.e., basement/crawlspace, walls or ceilings, carpets, or closets), ranged from 0% to 1% across the four seasons.

Thus, a higher percentage of the homeowners in this study reported observing mold in the bathroom (i.e., 13% in this study and 4%–7% in the UCB mail survey).

3.10 Relationships Between Home and IAQ Characteristics

This section fulfills the requirements stated in Study Objective 4, Examine the relationships among home ventilation characteristics, measured and perceived IAQ, and house and household characteristics. Note that because of the low number of homeowners reporting IAQ related perceptions and observations, there are insufficient data to prepare statistically meaningful correlations with home and IAQ characteristics.

3.10.1 Indoor Air Contaminant Emission Rates

The indoor emission rates of VOCs were calculated as the product of the indoor concentration minus the outdoor concentration and the outdoor air exchange rate. This calculation assumes that the penetration factor of VOCs in the outdoor air that is infiltrating through the building envelope was 1.0 and that there was no removal of VOCs from the indoor air unrelated to the outdoor air exchange rate (e.g., surface deposition/surface reaction, indoor air reactions, air filtration). These are relatively valid assumptions for the VOCs reported here.

Emission rates for $PM_{2.5}$ and NO_2 were not calculated, because these air contaminants can have significant removal mechanisms unrelated to the outdoor air exchange rate (e.g., surface deposition/surface reaction, indoor air reactions, air filtration). The emission rates for CO were also not calculated, because of the substantial uncertainty in the outdoor air concentrations caused by high outdoor humidity levels.

Table 45 (page 188) contains the calculated indoor emission rates of volatile organic compounds. The median indoor emission rates ranged from -0.03 μg/m^3-h for caprolactam to 11 μg/m^3-h for formaldehyde. The six highest maximum emission rates observed were: 139 μg/m^3-h for 1,4-dichlorobenzene, 65 μg/m^3-h formaldehyde, 44 μg/m^3-h for ethylene glycol, 32 μg/m^3-h for 2-butoxyethanol, 24 μg/m^3-h for toluene, and 20 μg/m^3-h for acetaldehyde and d-limonene.

The results of these indoor emission rate calculations for VOCs will used in the discussion of the variability observed in the multi-day and multi-season measurements.

3.10.2 Formaldehyde Emissions from Forced Air Units

Table 46 (page 189) contains the formaldehyde emission rate measurements from the FAUs in two Northern California homes: 017 and 120. The FAU formaldehyde emissions for Home 017 were measured in both the summer and winter. The FAU formaldehyde emissions for Home 120 were measured in just the winter. The FAU formaldehyde emissions were measured in a second summer session home, 033; however, a failure in the sample collection resulted in these data being lost.

The FAU emission rate of formaldehyde in Home 017 in the summer was 3,423 μg/h. This emission rate represents 21% of the total home emission rate as determined from the indoor and outdoor formaldehyde concentration measurements and the PFT measure of the outdoor air exchange rate. The FAU emission rate of formaldehyde in Home 017 in the winter was -3,381 μg/h, which is -56% of the total home emission rate. The negative emission rate measured in the winter is believed to be primarily the result of duct leakage associated with the return side of the FAU and the formaldehyde concentration in the attic air, which was lower than the concentration in the return air. The measured duct leakage for the FAU in this home was 4.8%. If the majority of this duct leakage were to be on the return side of the system (e.g., the fan cabinet panel), then leakage of the attic air, which has a much lower formaldehyde concentration than the return air (i.e., 2.0 μg/m^3 in the attic air and 15.3 μg/m^3 in the return air) into the return air could explain much of the lower formaldehyde concentration in the supply air, and hence the negative FAU emission rate. Also, the lower attic temperature (i.e., 67.0°F in the winter and 88.1°F in the summer) is expected to reduce the formaldehyde emissions from the fiberglass soundliner into the

FAU airstream and the formaldehyde emissions from materials in the attic (e.g., composite wood materials) into the attic air.

The FAU emission rate of formaldehyde in Home 120 in the winter was -7,681 μg/h, which is -151% of the total home emission rate. The reasons for the negative emission rates are believed to be similar to those for the Home 017 winter emission rate measurements. The measured duct leakage of the FAU in this home was 5.7%. The supply air concentration was also measured at a second location in this home. The supply air concentration at this second location was substantially lower (i.e., 65.7 $\mu g/m^3$ compared to 70.0 $\mu g/m^3$). Thus, the assumption in the emission rate calculation of perfect mixing of the air entering the FAU from the return air and from attic air entering through return air duct leaks does not appear to be a good assumption. Thus, the calculated emission rates of formaldehyde from the FAUs have a substantial amount of uncertainty. It does appear that in the summer, when attic temperatures can become elevated, that the FAU can transport formaldehyde into the home from either emissions of formaldehyde from fiberglass soundliner directly into the FAU airstream or from leakage of attic air with elevated formaldehyde concentrations into the return air of the FAU.

3.10.3 Multi-day Home Measurement Comparisons

The outdoor air exchange rate and indoor and outdoor VOC and aldehyde concentrations were measured in a total of four homes on three consecutive 24-hour periods: Thursday–Friday, Friday–Saturday, and Saturday–Sunday. The purpose of these multi-day consecutive measurements was to evaluate the day-to-day variations, including weekday and weekends. The four multi-day home measurements included one home in each season-region: Home 033 (Summer-North), Home 041 (Winter-South), Home 059 (Summer-South), and Home 099 (Winter-North). These four homes were each non-mechanically ventilated homes. Tables 47–50 (pages 190–193) contain the indoor and outdoor concentrations of VOCs, the outdoor air exchange rate, the indoor emission rates, and the absolute and relative variation in the emission rates. Note that the outdoor air contaminant measurements were only measured on the first day, Thursday–Friday, and thus to calculate the emission rates this measurement of the outdoor air contaminant concentrations were used to compute the indoor air contaminant emission rates for Days 2 and 3. Also, the PFT measurement for Day 1 in Home 099 was lost due to a lab error and thus there are no emission rates calculated for Day 1.

The variations in the indoor concentrations are expected to be largely the result of the variations in the outdoor air exchange rate and the emission rates of indoor sources, especially those sources that are not continuous, such as those related to intermittent activities such as cleaning, cooking, air fresheners, etc.

The relative standard deviations of the outdoor air exchange rates were 0.04 for Home 041, 0.05 for Home 099, 0.28 for Home 059, and 0.38 for Home 033, with an average of 0.19 for the four homes. The average relative standard deviation of the indoor air contaminant concentrations were 0.12 for Home 099, 0.30 for Home 041, 0.44 for Home 059, and 0.50 for Home 033, with an average of 0.34 for the four homes. Thus, as the variation in the outdoor air exchange rates increased, so did the variation in the indoor air contaminant concentrations.

The average absolute variation of the indoor air contaminant emission rates were 0.6 $\mu g/m^3$-h for Home 099, 0.9 $\mu g/m^3$-h for Home 033, 1.0 $\mu g/m^3$-h for Home 041, and 2.5 $\mu g/m^3$-h for Home 059, with an average of 1.3 $\mu g/m^3$-h for the four homes.

By comparing the variations of the indoor air contaminant emission rates with the source activity logs prepared by the homeowners, it is possible to develop hypotheses as to the identity of the indoor sources. For each home the research team looked at the indoor air contaminant emission rates with substantial variations (i.e., more than 2 $\mu g/m^3$-h absolute variation and with more than a 0.50 relative standard deviation) and examined the occupant source activity logs to see if there were any sources that might explain the variation in the emission rates.

For Home 033, d-limonene was the VOC with the most substantial variation in the indoor emission rate, as defined above, with emission rates of 2.2 $\mu g/m^3$-h on Thursday–Friday, 1.8 $\mu g/m^3$-h on Friday–Saturday, and 4.9 $\mu g/m^3$-h on Saturday–Sunday. An examination of the source activity logs did not reveal and activities that might explain this increase. Note that d-limonene is often found in deodorizers and household cleaning chemicals.

For Home 041, 2-butoxyethanol was the VOC with the most substantial variation in the indoor emission rate, with emission rates of 5.8 $\mu g/m^3$-h on Thursday–Friday, 0.8 $\mu g/m^3$-h on Friday–Saturday, and 0.6 $\mu g/m^3$-h on Saturday–Sunday. An examination of the source activity logs indicated that on Thursday–Friday, and not on the other two days, there was 20 minutes of sweeping/dusting with anti-bacterial wipes, which is a potential source of 2-butoxyethanol, a common ingredient in cleaning chemicals.

For Home 059, hexanal was the VOC with the most substantial variation in the indoor emission rate, with emission rates of 4.7 $\mu g/m^3$-h on Thursday–Friday and 5.8 $\mu g/m^3$-h on Friday–Saturday, and 1.2 $\mu g/m^3$-h on Saturday–Sunday. An examination of the source activity logs did not reveal any activities that might explain this variation.

For Home 099, there were no volatile organic compounds with substantial variations in the indoor emission rates.

3.10.4 Multi-Season Home Measurement Comparisons

The outdoor air exchange rate and indoor and outdoor air contaminant concentrations were measured in a total of four homes for three 24-hour periods, during three different seasons; summer, fall, and winter. The purpose of these multi-season measurements was to evaluate the season-to-season variations. The four multi-season home measurements included four homes in the North region; Home 005, Home 006, Home 013, and Home 019. These four homes were each non-mechanically ventilated homes. Tables 51–54 (pages 194–197) contain the indoor and outdoor concentrations of VOCs, the outdoor air exchange rate, the indoor emission rates, and the absolute and relative variation in the emission rates. Note that for Home 013, the homeowners were unable to participate in the winter field session, thus there are only measurements for two seasons, summer and fall. Also, the PFT measurement for Day 1 in Home 019 resulted in an unrealistically low air exchange rate (i.e., 0.03 ach) and thus was deleted as an unreliable measurement. For this reason there are no emission rates calculated for Day 1 in Home 019.

As with the multi-day homes, the variations in the indoor concentrations of these multi-season homes are expected to be largely the result of the variations in the outdoor air exchange rate and the emission rates of indoor sources, especially those sources that are not continuous, such as those related to intermittent activities such as cleaning, cooking, air fresheners, etc. The variations in the outdoor air exchange rates, and thus the indoor air contaminant concentrations, are expected to be higher for the multi-season homes than the multi-day homes, with outdoor air exchange rates being lower and the indoor air contaminant concentrations higher in the winter season when windows are more often kept closed.

The relative standard deviations of the outdoor air exchange rate were 0.34 for Home 005, 0.64 for Home 019, 0.75 for Home 006, and 0.95 for Home 013, with an average of 0.67 for the four homes. The average relative standard deviation of the indoor air contaminant concentrations were 0.45 for Home 006, 0.52 for Home 013, 0.59 for Home 005, and 0.82 for Home 019, with an average of 0.60 for the four homes.

Thus, the variations of both the outdoor air exchange rate and indoor air contaminant concentrations were much higher for these multi-season homes then for the multi-day homes. The average relative standard deviation of the outdoor air exchange rates was 3.5 times higher for the multi-season homes, and the average relative standard deviation of the indoor air contaminant concentrations was 1.8 times higher.

The average absolute variation of the indoor air contaminant emission rates were 0.50 μg/m^3-h for Home 019, 1.5 μg/m^3-h for Home 006, 4.1 μg/m^3-h for Home 013, and 6.3 μg/m^3-h for Home 005, with an average of 3.1 μg/m^3-h for the four homes, which is 2.6 times higher that the average of 1.2 μg/m^3-h for the four multi-day homes.

Thus, the larger variations in the indoor air contaminant concentrations in the multi-season homes appears to be the combination of larger variations in the outdoor air exchange rates and the indoor air contaminant emission rates.

For each home the research team looked at the indoor air contaminant emission rates with substantial variations (i.e., more than 2 μg/m^3-h absolute variation and with more than a

0.50 relative standard deviation) and examined the occupant source activity logs to see if there were any sources that might explain the variation in the emission rates.

For Home 005, 1,4-dichlorobenzene, was the VOC with the most substantial variation in the indoor emission rate, with emission rates of 72 μg/m^3-h in the summer, 1.9 μg/m^3-h in the fall, and 0.8 μg/m^3-h in the winter. An examination of the source activity logs did not reveal any activities that might explain this increase. Note that 1,4-dichlorobenzene is often found in mothballs, although the homeowners did not report in the Occupant Questionnaire any use of mothballs.

For Home 006, d-limonene was the VOC with the most substantial variation in the indoor emission rate, with emission rates of 1.6 μg/m^3-h in the summer, 0.9 μg/m^3-h in the fall, and 4.1 μg/m^3-h in the winter. An examination of the source activity logs indicated that the occupants used furniture polish for 15 minutes and cleaning chemicals for 30 minutes during the winter field session but not in either the summer or fall field sessions. Note that d-limonene is often found in deodorizers and household cleaning chemicals.

For Home 013, toluene was the VOC with the most substantial variation in the indoor emission rate, with emission rates of 18 μg/m^3-h in the summer, and 50 μg/m^3-h in the fall. An examination of the source activity logs indicated that the occupants used two plug-in air fresheners for 24 hours during the fall field session but not in the summer field session. Note that toluene is found in some air fresheners.

For Home 019, there were no VOCs with substantial variations in the indoor emission rates.

3.10.5 Group Comparisons

Group comparisons were prepared for indoor formaldehyde and acetaldehyde concentrations, outdoor air exchanges rates, and window usage. Formaldehyde and acetaldehyde were selected for these analyses, as these were two air contaminants that most frequently exceeded recommended indoor concentration guidelines. Note that because of the small number of homes in the sample groups, these comparisons should only be considered as suggestive of differences. Multivariate analyses need to be done to further establish any differences between the groups.

The group comparisons consisted of homes in the North versus South regions, homes in summer versus winter seasons, and homes without mechanical outdoor air systems versus homes with either pure DOA or pure HRV outdoor air ventilation systems. For the seasonal group comparison the research team used the 19 seasonal repeat homes with formaldehyde and acetaldehyde measurements (one of the 20 seasonal repeat homes did not have a formaldehyde or acetaldehyde measurement as a result of a sampler failure).

Homes with nighttime cooling systems, evaporative coolers, and window fans were excluded from these analyses.

According to the K-S statistic analyses, the distributions of indoor formaldehyde and acetaldehyde concentrations, outdoor air exchange rates, and window usage were found to be not normally distributed. The K-S statistic was repeated with several functions applied to the distributions. If the K-S statistic returned a result with a probability greater than 0.05, then the distribution was determined to be normal. The formaldehyde and acetaldehyde concentrations were found to be lognormal; the inverse of the outdoor air exchange rate was found to be normal; and the square root of window opening, where different than zero, was found to be normal. The results of these analyses are summarized in Table 55 (page 198), along with the probability that the distribution is normal. Figures 29–32 (pages 128–131) present the cumulative frequency plots of the normalized data.

3.10.5.1 Formaldehyde and Acetaldehyde and Group Comparisons

Table 56 (page 199) contains the group analyses for indoor formaldehyde and acetaldehyde concentrations. For the t-test comparisons of differences in the group mean concentrations the research team used the normalized data; the log of the indoor formaldehyde concentrations and the log of the indoor acetaldehyde concentrations. If the probability of no difference was less than 0.05, then the means were considered to be different. Note that the number of homes with HRV systems in these group comparisons was very small (i.e., n=4), and thus only very large differences in the group means can be identified.

<u>North-South Homes</u>. For this comparison only those homes without mechanical outdoor air ventilation systems were compared. The mean log of the indoor formaldehyde concentration was found to be significantly higher in North homes than in South homes ($p = 0.001$). The mean log of the indoor acetaldehyde concentration was not found to be significantly different in North homes and South homes.

<u>Summer-Winter Homes</u>. The mean log of the indoor formaldehyde acetaldehyde concentrations were not found to be significantly different in summer homes and winter homes.

<u>Homes With and Without Mechanical Outdoor Air Ventilation Systems</u>. The mean log of the indoor formaldehyde and acetaldehyde concentrations were found to be significantly higher in homes with DOA mechanical outdoor air systems than in non-mechanically ventilated homes ($p=0.0001$ and $p=0.005$ respectively). The mean log of the indoor formaldehyde and acetaldehyde concentrations were not found to be significantly different in homes with HRV mechanical outdoor air systems and in non-mechanically ventilated homes. The low number of HRVs (i.e., n=4) precluded identifying the substantially lower mean indoor log concentrations of formaldehyde and acetaldehyde in the HRV homes as being statistically significant.

Homes With DOA and HRV Outdoor Air Ventilation. The mean log of the concentration of formaldehyde and acetaldehyde was found to be significantly higher in homes with DOA mechanical outdoor air systems than in homes with HRV mechanical outdoor air systems ($p=0.05$ and $p=0.02$ respectively).

3.10.5.2 Outdoor Air Exchange Rate and Window Usage Group Comparisons

Table 57 (page 200) contains the group analyses for outdoor air exchange rates and window usage. The outdoor air exchange rate consisted of the 24-hour PFT measurement and the window usage consisted of the 24-hour log of the ft^2-hrs of window/door usage. For the t-test comparisons of differences in the group mean outdoor air exchange rates and window usage the research team used the normalized data; inverse air changes per hour and the square root of the window usage. If the probability of no difference was less than 0.05, then the means were considered to be different.

North-South Homes. For this comparison only those homes without mechanical outdoor air ventilation systems were compared. The mean inverse of the outdoor air exchange rate and the mean square root of the window usage was found to not be significantly different in North homes and South homes.

Summer-Winter Homes. The mean inverse of the outdoor air exchange rate was found to not be significantly different in summer homes and winter homes. The mean square root of the window usage was found to be significantly higher in summer homes than in winter homes ($p=0.02$).

Homes With and Without Mechanical Outdoor Air Ventilation Systems. The mean inverse of the outdoor air exchange rate was found to not be significantly different in DOA mechanical outdoor air systems and non-mechanically ventilated homes. The mean inverse of the outdoor air exchange rate was found to be significantly higher in homes with HRV mechanical outdoor air systems than in non-mechanically ventilated homes ($p = 0.002$). The mean square root of the window usage was found to not be significantly different in either DOA or HRV mechanical outdoor air systems when compared to the non-mechanically ventilated homes.

Homes With DOA and HRV Outdoor Air Ventilation Systems. The mean inverse of the outdoor air exchange rate was found to be significantly lower in HRV than DOA mechanical outdoor air systems ($p=0.008$). The mean square root of the window usage was found to not be significantly different in HRV and DOA mechanical outdoor air systems.

3.11 Formaldehyde and Acetaldehyde Concentration Correlations

Correlation analyses were prepared for indoor formaldehyde and acetaldehyde concentrations with home characteristics and indoor and outdoor environmental conditions. Formaldehyde and acetaldehyde were selected for these analyses, because these were the two air contaminants that most frequently exceeded recommended indoor concentration guidelines.

The six home characteristics included:

- home age (years)
- composite wood loading (ft^2 per 1,000 ft^3 of indoor air volume)
- new cabinetry (within six months)
- new furniture (within six months)
- air fresheners (presence or absence)
- outdoor air exchange rate (ach)

The four environmental conditions included:

- indoor air temperature (^oF)
- indoor relative humidity (%)
- outdoor air temperature (^oF)
- outdoor relative humidity (%)

The composite wood loading includes the total composite wood area in square feet observed to be associated with cabinetry/furniture and the finishes of walls, ceilings, and floors divided by the indoor air volume (i.e., ft^2 of composite wood per 1,000 ft^3 of indoor air volume).

The research team prepared both Pearson correlations for those variables that could be normalized as well as Spearman correlations, which do not require the sample populations be normally distributed.

Outdoor air temperature and relative humidity, indoor air temperature, and home age data were found to be normally distributed. As previously discussed, according to the K-S statistic analyses, the distributions of indoor formaldehyde and acetaldehyde concentrations, outdoor air exchange rates, window usage, composite wood loading, and indoor air relative humidity were found to be not normally distributed. The K-S statistic was repeated with several functions applied to the distributions. The formaldehyde and acetaldehyde concentrations were found to be lognormal; the inverse of the outdoor air exchange rate (i.e., outdoor air residence time) was found to be normal; and the square root of window opening, where different than zero, was found to be normal. The log of the composite wood loading was found to be log normal, and the indoor air relative humidity squared was found to be log normal. The results of these analyses are summarized in Table 55 (page 198) along with the probability that the distribution is normal. Figures 33–38 (pages 132–137) present the cumulative frequency of the normalized data.

Tables 58 and 59 (pages 201 and 202) contain the correlations for formaldehyde and acetaldehyde concentrations, respectively, with the six home characteristics and four environmental conditions. If the probability of no correlation was less the 0.05, then a correlation was concluded to possibly exist. Note that since these are bivariate analyses, the establishment of a possible correlation between two variables does not indicate that there is a causal relationship. Other factors may be determined to be equally or more important when analyzed together in a multivariate analyses, which is beyond the scope of this study, but is recommended for future analyses.

Figures 39–45 (pages 138–144) are scatter plots of the indoor formaldehyde and acetaldehyde concentrations and the three continuous home characteristic variables, home age, composite wood loading, and outdoor air exchange rate, and the four environmental conditions.

For both formaldehyde and acetaldehyde concentrations, one home characteristic—outdoor air exchange rate—was determined by both the Pearson and Spearman correlation analyses to have a statistically significant correlation. This correlation was relatively strong, with probabilities of no correlation less than 0.0001, as determined by both Pearson and Spearman correlation analyses. The correlation coefficients indicate that indoor formaldehyde concentrations correlate negatively with the outdoor air exchange rates (i.e., as outdoor air exchange rates increase the indoor concentrations of formaldehyde decrease). Note since the Pearson correlation coefficient uses the normalized inverse outdoor air exchange rate (i.e., the outdoor air residence time), the positive correlation coefficients represents a negative correlation with outdoor air exchange rate.

For formaldehyde concentrations, one environmental condition, indoor air temperature, was determined by both the Pearson and Spearman correlation analyses to have a statistically significant correlation. The correlation coefficients indicate that indoor formaldehyde concentrations correlate positively with the indoor air temperature (i.e., as indoor air temperatures increase, the indoor concentrations of formaldehyde increase).

Not as expected, both the Pearson and Spearman correlations produced negative correlations for composite wood loading and acetaldehyde indoor concentrations, and no significant correlation for composite wood loading and formaldehyde indoor concentrations, despite the knowledge that composite wood is an indoor emitter of both formaldehyde and acetaldehyde. This may be the result of incompleteness of the recovery of this variable in the field from the visible inspection by the field team. Composite wood could not always be accurately identified because of coverings by laminate or paint. In addition, the inspectors only estimated the square footage of composite wood from furniture and cabinetry. Other substantial amounts of composite wood loading that are common in many of these homes, but are difficult to quantify in the limited time available to the inspectors, include plywood and oriented strand board (OSB) in walls, subfloors, and attics and medium density fiberboard in baseboards, window shades, interior doors, and window and door trims. Also, the inspectors estimated the areas of composite wood without separately distinguishing those areas that were exposed and those areas that were covered with laminate.

The variance introduced by the impact of outdoor air exchange rates upon the indoor concentrations of formaldehyde and acetaldehyde may also be contributing to the lack of an observed significant positive correlation between composite wood loading and the indoor concentrations of formaldehyde and acetaldehyde.

3.12 Incentives and Barriers that Influence People's Use of Ventilation

This section fulfills the requirements stated in Study Objective 5, Identify the incentives and barriers that influence people's use of windows, doors, and mechanical ventilation devices for adequate air exchange.

The Occupant Questionnaire on mechanical ventilation systems focused exclusively on the mechanical outdoor air ventilation systems. Tables 60 and 61 (pages 203 and 204) summarize the responses to these questions from homes with either a DOA or HRV mechanical outdoor air system and with completed responses to questions, excluding those with only nighttime cooling systems (e.g., WHF, RAD), evaporative cooling systems, or window fans. The total of 26 homes with mechanical outdoor air systems included 17 DOA systems and 9 HRV systems.

A total of 78% stated that the operation of the system was explained to them when they bought or moved into the house. In addition, 63% responded that they understood how the system works, and 83% stated that they understood how to operate the system properly.

With respect to questions how they typically operate the system, 32% reported continuous operation in the summer, 36% in the fall, 18% in the winter, and 27% in the spring.

With respect to the question of "Why did you choose the system?," 91% of the respondents replied that the system "came with the house."

With respect to the question of "What do you like about the system?," the three most frequent responses were, "Fresh air" (52%), "Quiet" (48%), and "Reduced concern about indoor air quality" (26%).

The written descriptions accompanying the "Other" reasons that the homeowners did like about the mechanical outdoor air systems, along with the system type and Home ID, were:

- "I can shut off one of the 2 zones for economy." (DOA-2 systems, Home 043)

- "House does not feel/smell stuff or that it has been closed." (DOA, Home 102)

- "Clears moisture from baths and laundry." (HRV, Home 104)

With respect to the question "What don't you like about the system ?," the four most frequent responses were, "Not effective" (32%), "Too drafty" (26%), "Too noisy" (26%), and "Other" (26%).

The written descriptions accompanying the "Not effective" and "Other" reasons that the homeowners did not like about the mechanical outdoor air systems, along with the system type and Home ID, were:

- "Needs to turn on with HVAC system, not every 45 mins. Automatically." (DOA, Home 001)

- "Need to go into attic to clean the filter." (HRV, Home 017)

- "Unit is difficult to reach, expensive yearly maintenance service." (HRV, Home 018)

- "House is always stuffy, cannot feel fresh air, not able to shut off, always running if air/heater is off." (DOA, Home 021)

- "Never understood how to use it." (DOA, Home 021)

- "Brings in hot air in the summer and cold air in the winter." (HRV, Home 022)

- "One zone does not shut off when it reaches its program." (DOA-2 systems, Home 043)

- "It is on a 90 min automatic cycle. It brings in hot air in summer, cold air in winter, air w/smoke in it & air during aerial spraying for West Nile viruses." (DOA, Home 102).

- "Dust seems to still get on the table tops." (HRV, Home 104)

- "It does not heat & cool the house evenly. Half the house is fairly comfortable and the other half is not." (DOA, Home 109)

With respect to the question of “Please list any additional problems or provide additional comments you have on the system,” the following are the written descriptions, along with the system type and Home ID:

- “The thermostat works when it wants to not when he wants it to, it's like it has a mind of its own. They already replaced it once and it didn't fix the problem.” (DOA, Home 008)

- “I have no idea how the system works. The only controls that I am aware of are for heating and cooling.” (DOA, Home 011)

- “Should be able to clean filters more easily, especially since this is a senior development. More reason clean filters.” (HRV, Home 017).

- “Not able to shut off system, never feel fresh air coming from outside, always hot/stuffy in house; cooler outside.” (DOA, Home 021)

- “It needs to have a switch where the home owner can shut it off.” (DOA, Home 102).

- “Colder type air comes out of the vents during the winter along with the heated air, thereby making it uncomfortable if you are positioned near the vents? Opposite in the summer.” (DOA, Home 109)

- “Did not know one of my ducts was closed.” (DOA, Home 110).

3.13 Incentives and Barriers Related to People’s Purchases and Practices that Improve IAQ

This section fulfills the requirements stated in Study Objective 6, Identify the incentives and barriers related to people’s purchases and practices that improve IAQ, such as the use of low-emitting building materials and improved air filters.

The Occupant Questionnaire contained a number of questions focused upon home IAQ related improvement choices. Table 62 (page 205) summarizes the responses to these questions. A total of 24% of the 105 respondents to this question stated “none” in response to the question “What special measures or choices have you or the builder taken to improve the quality of the air in your home?”.

The four most frequent responses to improvements undertaken were: “Hard flooring instead of carpeting” (33%), “Carbon monoxide alarm” (28%), “High efficiency vacuum cleaner with special features such as filters to trap more particles” (27%), and “Upgrade my central air filter” (25%).

With respect to the question of “Other” Home IAQ Improvements, the following are the written descriptions, along with the Home ID:

- “Ceramic tile and linoleum to replace all but bedroom carpeting.” (Home 002).
- “Hard flooring in kitchen entryway & part of hallway.” (Home 015).
- “24-hr fans: 2 bathrooms/utility room to prevent mold.” (Home 016).
- “Smartvent.” (Home 018).
- “Smartvent.” (Home 019).
- “All bath fans are on 60-min. timers; whole house fan on 12-hr. timer.” (Home 034).
- “Changed original air filter.” (Home 048).
- “Methane gas mitigation system - builder installed.” (Home 054).
- “Living Air portable cleaner system, Orek, Sharper Image air cleaners.” (Home 069).
- “Master cool evap cooler for fresh air.” (Home 070).
- “Switched to crystal (dustless) cat litter.” (Home 077).
- “We usually open windows and keep them open. During the last week its been cold so we've not done so as usual.” (Home 079).
- “Whole house fan.” (Home 088).
- “Hard flooring in downstairs.” (Home 092)
- “Air purifiers in bedrooms (4).” (Home 105).
- “Cleaning supplies natural/nontoxic, plant in most rooms.” (Home 121).

3.14 Recent Developments Related to Codes, Regulations, and Guidelines

Recently there have been several changes to codes, regulations, and guidelines that are noteworthy with respect to the data collected in this study.

The OEHHA RELs for formaldehyde and acetaldehyde were revised in December 2008 (OEHHA 2008b). These revisions reflect scientific knowledge and techniques developed since the previous guidelines were prepared, and in particular, explicitly include consideration of possible differential effects on the health of infants, children and other sensitive subpopulations. In addition to the previously defined Acute and Chronic RELs, the revisions include establishment of 8-hour RELs.

For formaldehyde, the Acute REL was reduced from 94 $\mu g/m^3$ to 55 $\mu g/m^3$. The interim 8-hour REL was reduced from 33 $\mu g/m^3$ to 9 $\mu g/m^3$ and is no longer an interim standard. The Chronic REL was increased from 3 $\mu g/m^3$ to 9 $\mu g/m^3$.

For formaldehyde, the percentage of homes exceeding the Acute REL increases from 6.7% to 28% for the new REL. The percentage of homes exceeding the 8-hour REL increases from 59% to 98%. The percentage of homes exceeding the Chronic REL decreases from 100% to 98%.

For acetaldehyde, the Acute REL, for which previously there was no established level, was set at 470 $\mu g/m^3$, the 8-hour REL, for which previously there was no established level, was set at 300 $\mu g/m^3$, and the Chronic REL was increased from 9 $\mu g/m^3$ to 140 $\mu g/m^3$.

For acetaldehyde the percentage of homes exceeding the Chronic REL decreases from 82% to 0% for the new higher exposure levels, and 0% of the homes exceed the new 8-hour REL and the new Chronic REL.

In April 2007, the California Air Resources Board adopted an airborne toxics control measure (ATCM) to reduce formaldehyde emissions from composite wood products including hardwood plywood (HWPW), particleboard (PB), medium density fiberboard (MDF), and also furniture and other finished products made with these wood products (California Air Resources Board 2007b). This ATCM established the most stringent, production-based, formaldehyde standards in the world. ARB's evaluation of formaldehyde exposure in California found that one of the major sources is from inhalation of formaldehyde emitted by composite wood products containing urea-formaldehyde resin. Much of this HWPW, PB, and MDF is used to make furniture, cabinets, shelving, countertops, flooring and moldings.

This ATCM was approved by the Office of Administrative Law on April 18, 2008 (California Code of Regulations 2008). The Phase 1 implementation date is scheduled for January 1, 2009. A Phase 2 set of lower emissions rates is scheduled for implementation January 1, 2010, for hardwood plywood with veneer core and January 1, 2011, for particleboard and medium density fiberboard.

The California Energy Commission (2008a) adopted the 2008 Building Energy Efficiency Standards on April 23, 2008, and these standards become effective August 1, 2009. The new 2008 standards require all low-rise residential buildings to have a mechanical outdoor air ventilation system. The mechanical outdoor air ventilation system requirements in the new 2008 standard are an adoption of ASHRAE Standard 62.2-2007, with the exception that use of openable windows for outdoor ventilation in place of mechanical outdoor air ventilation, while permitted by ASHRAE, is not an acceptable option. The ASHRAE mechanical outdoor air ventilation rates discussed in this report, ASHRAE 62.2-2004, are identical to the ASHRAE 62.2-2007 (ASHRAE 2007) rates and the new California 2008 Building Energy Efficiency Standards.

In addition, the new 2008 California Title 24 Alternative Calculation Method (ACM) Manual (California Energy Commission 2008b) no longer requires mechanical outdoor ventilation of 0.047 cfm/ft^2 in homes that builders are taking credit for building a home with an SLA less than 3.0. The new 2008 Building Energy Efficiency Standards now require that all homes, regardless of the SLA, have mechanical outdoor air ventilation.

ASHRAE published addenda to ASHRAE Standard 62.2-2007 in 2008 (ASHRAE 2008). These 2008 addenda included Addendum b, which provides changes to Table 4.2, "Ventilation Effectiveness for Intermittent Fans." This addendum also changed the requirement that intermittent mechanical outdoor air systems operate a minimum of 1 hour every 12 hours to a minimum operation of once per 24 hours and a minimum fractional on-time of 0.10. The new California 2008 Building Energy Efficiency Standards, which cites ASHRAE 62.2-2007, do not include this addendum.

For the three DOA systems in this study with operational fan cyclers, the new Addendum b ventilation effectiveness factors result in decreased outdoor airflow rate requirements. The measured outdoor airflow rates in these three homes were all still well below the requirements, as calculated according to the new Addendum b. Previously these three homes had mechanical outdoor airflow rates that were just 3%, 7%, and 8% of the intermittent flow rate requirements, and using the calculations in Addendum b the mechanical outdoor airflow rates are 9%, 10%, and 26% of the intermittent flow rate requirements.

Ventilation rates and indoor air contaminant concentrations were re-calculated using the new Addendum b ventilation effectiveness factors for intermittent ventilation systems and the modeling scenario utilized in Section 3.6.1. The ventilation effectiveness factor was increased by Addendum b from 0.33 to 0.65. This resulted in a reduction of the required outdoor airflow rate for intermittent mechanical systems, and further increases in the indoor air contaminant concentrations. The 24-hour average indoor concentration was 34% higher than that with a continuous system, up from the 29% higher concentration with the pre-Addendum b ventilation effectiveness factor. The maximum air contaminant concentration was 222% higher than that with a continuous system, up from the 220%

higher concentration with the pre-Addendum b ventilation effectiveness factor. Thus, for the modeling scenario examined, the new Addendum b ventilation effectiveness factor resulted in 4% higher 24-hour average indoor air contaminant concentrations and similar (i.e., less than 1% higher) maximum concentrations.

The intent of the changes to the intermittent ventilation effectiveness factors in Addendum b was to correct these factors such that the resulting 24-hour time-weighted average indoor contaminant concentrations are equivalent to those for a continuously operated ventilation system. However, as the analyses above indicate, the Addendum b intermittent ventilation effectiveness factors provided higher 24-hour time-weighted average indoor contaminant concentrations. The ASHRAE 62.2 Standards Committee has acknowledged this error with the Addendum b intermittent ventilation effectiveness factors and is currently pursuing a correction.

Figure 3. Locations of homes for the summer and winter 2006–2007 field sessions in Northern and Southern California.

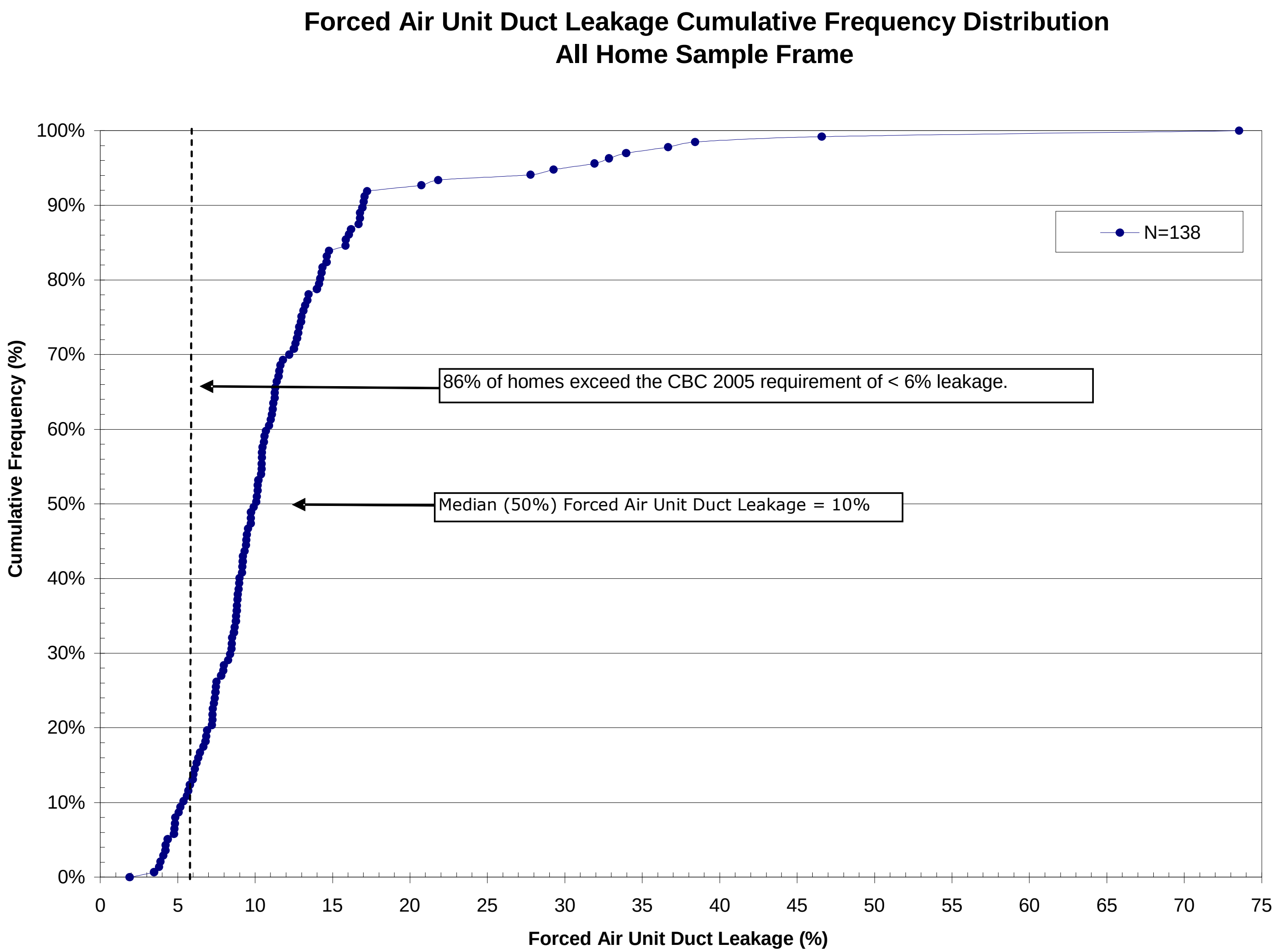


Figure 4. Forced air duct leakage cumulative frequency distribution - All Home Sample Frame.

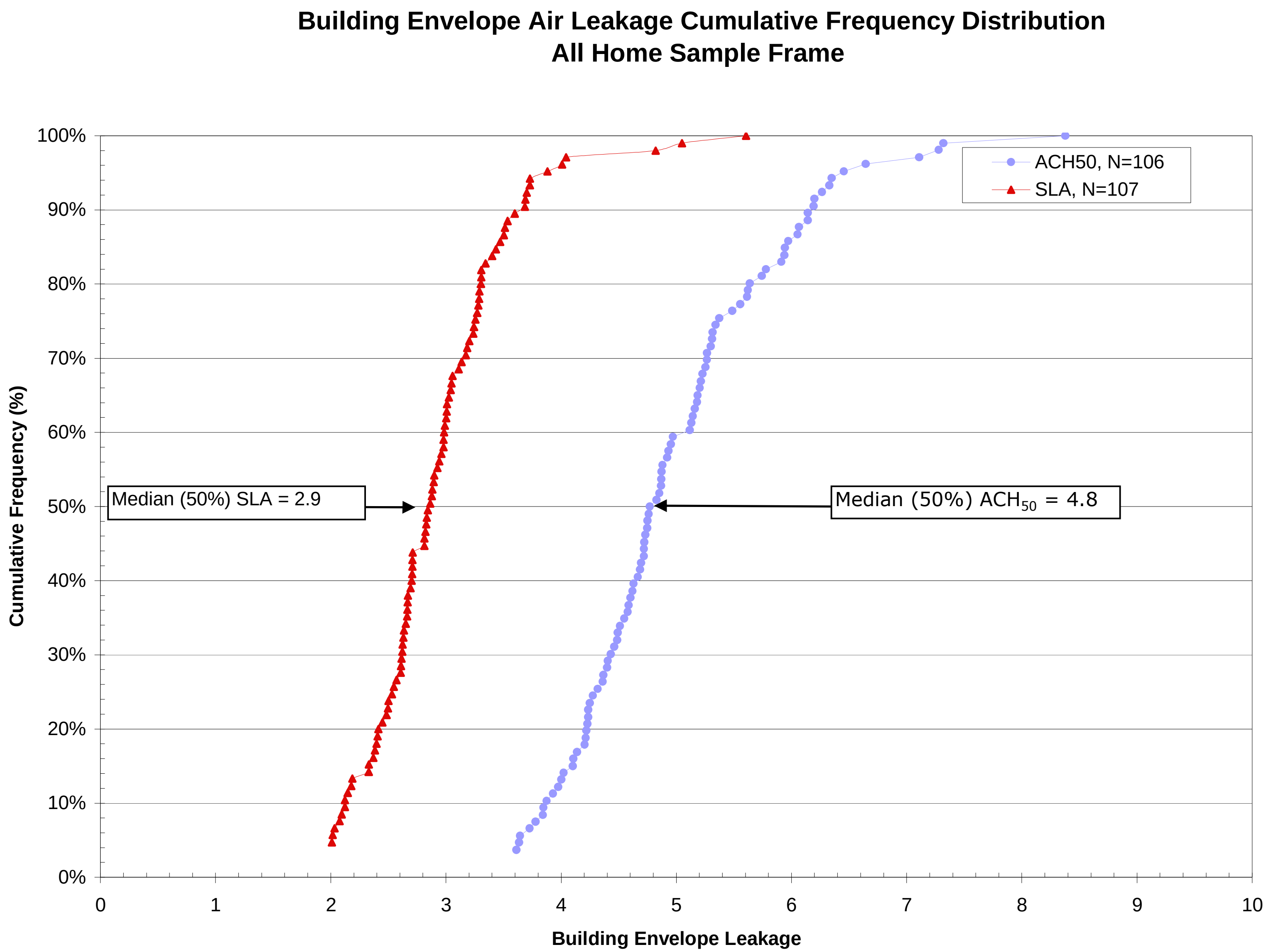


Figure 5. Building envelope air leakage cumulative frequency distribution – All Home Sample Frame.

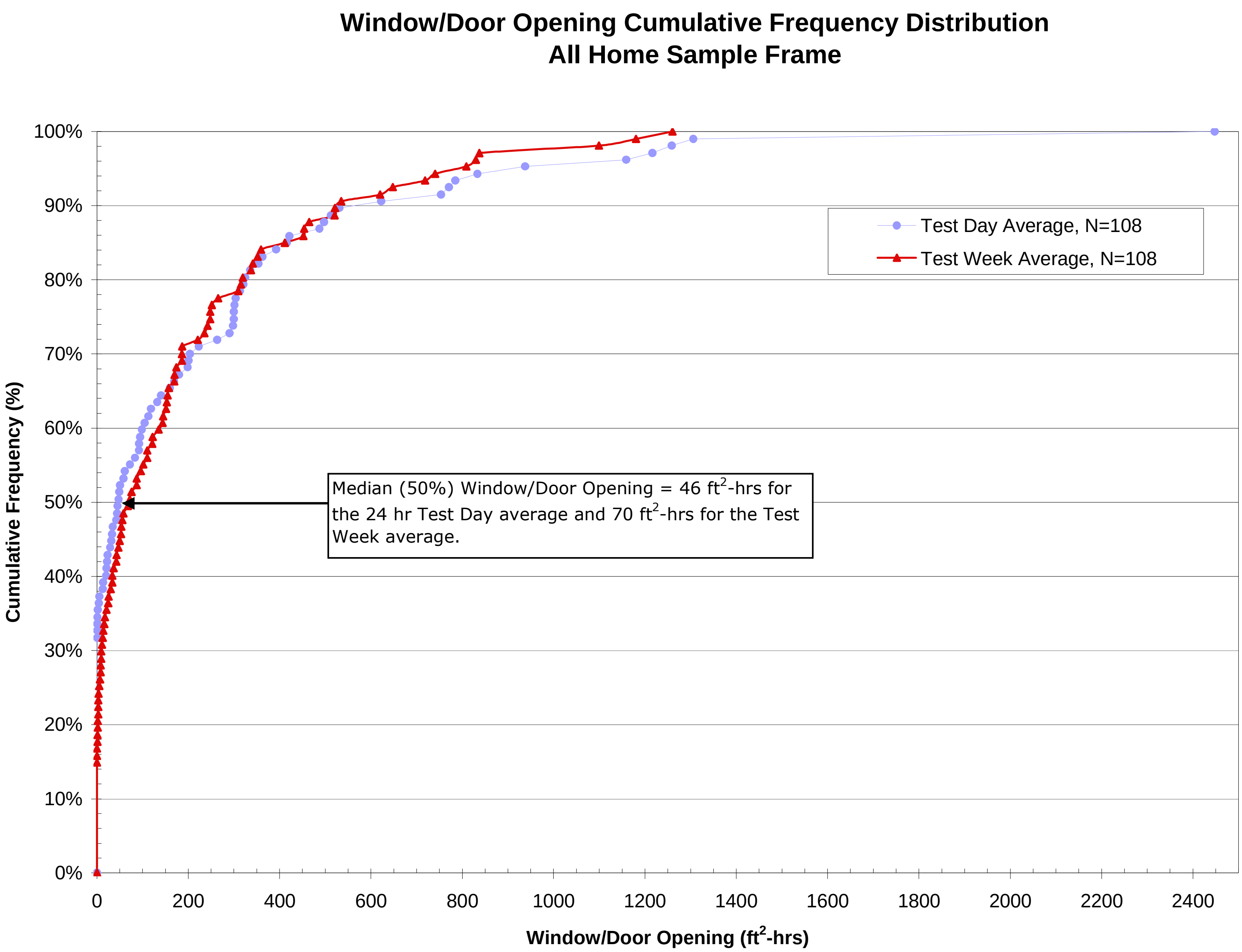


Figure 6. Window and door opening cumulative frequency distribution – All Home Sample Frame.

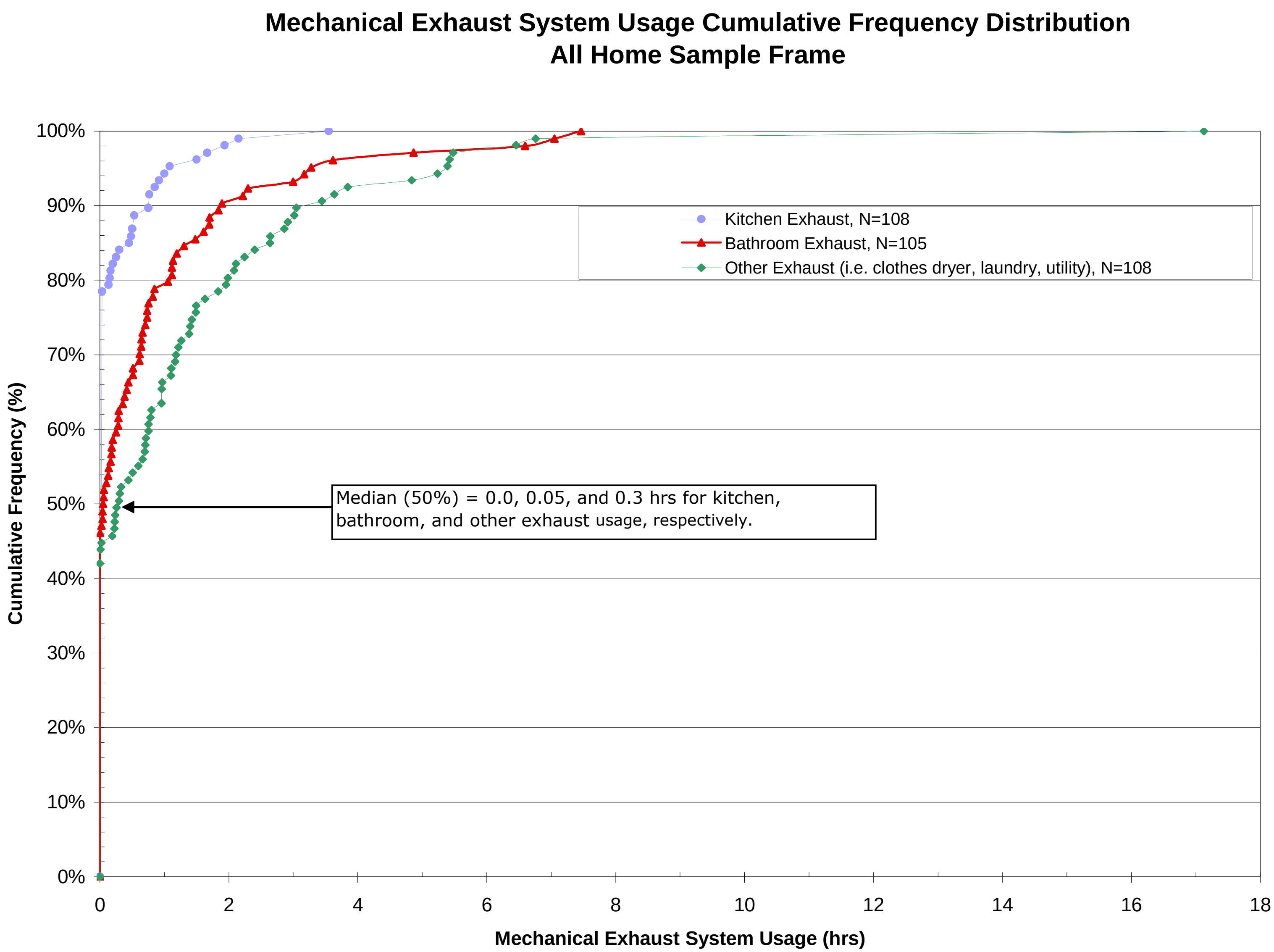


Figure 7. Mechanical exhaust system usage cumulative frequency distribution – All Home Sample Frame.

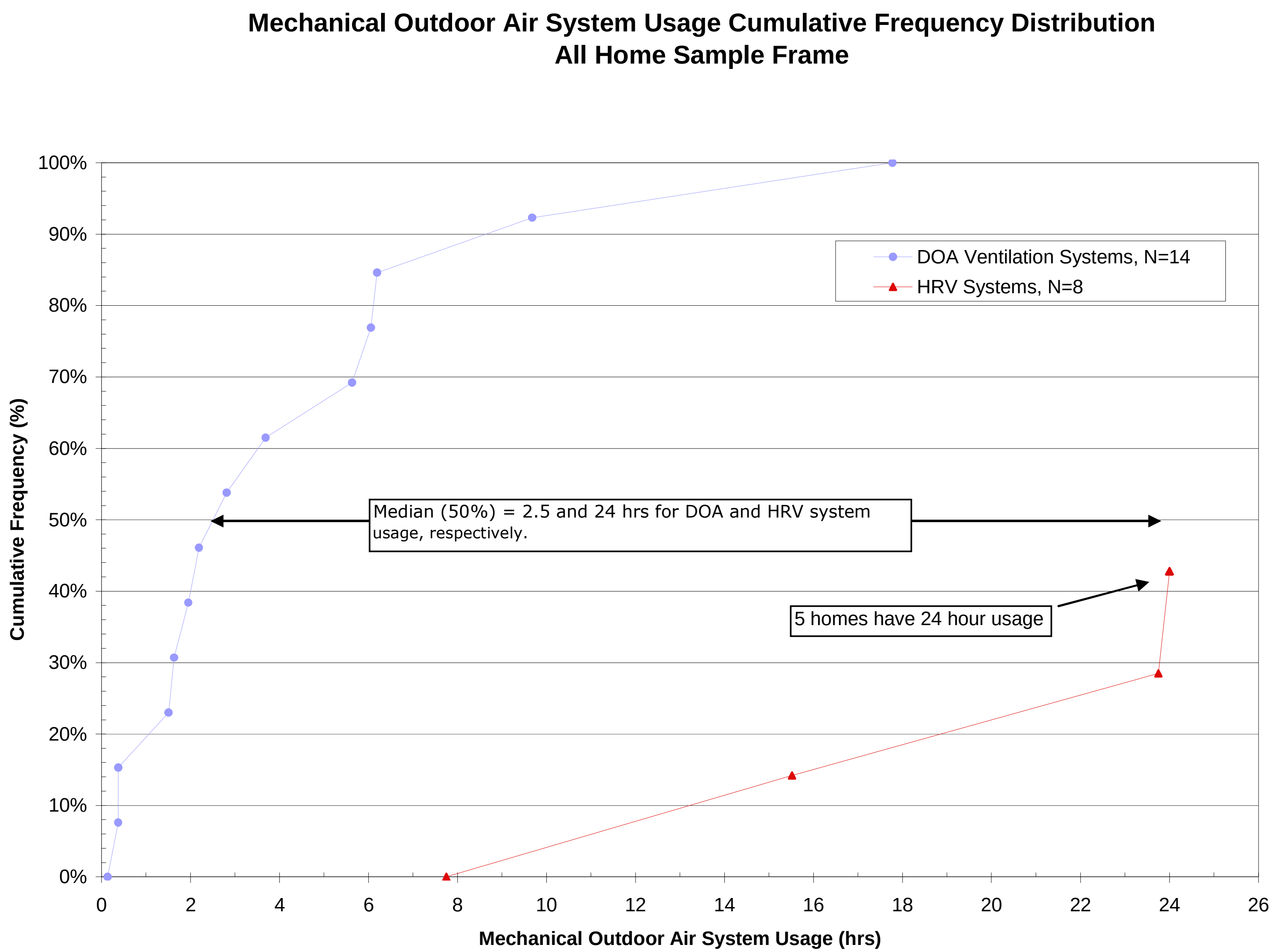


Figure 8. Mechanical outdoor air system usage cumulative frequency distribution – All Home Sample Frame.

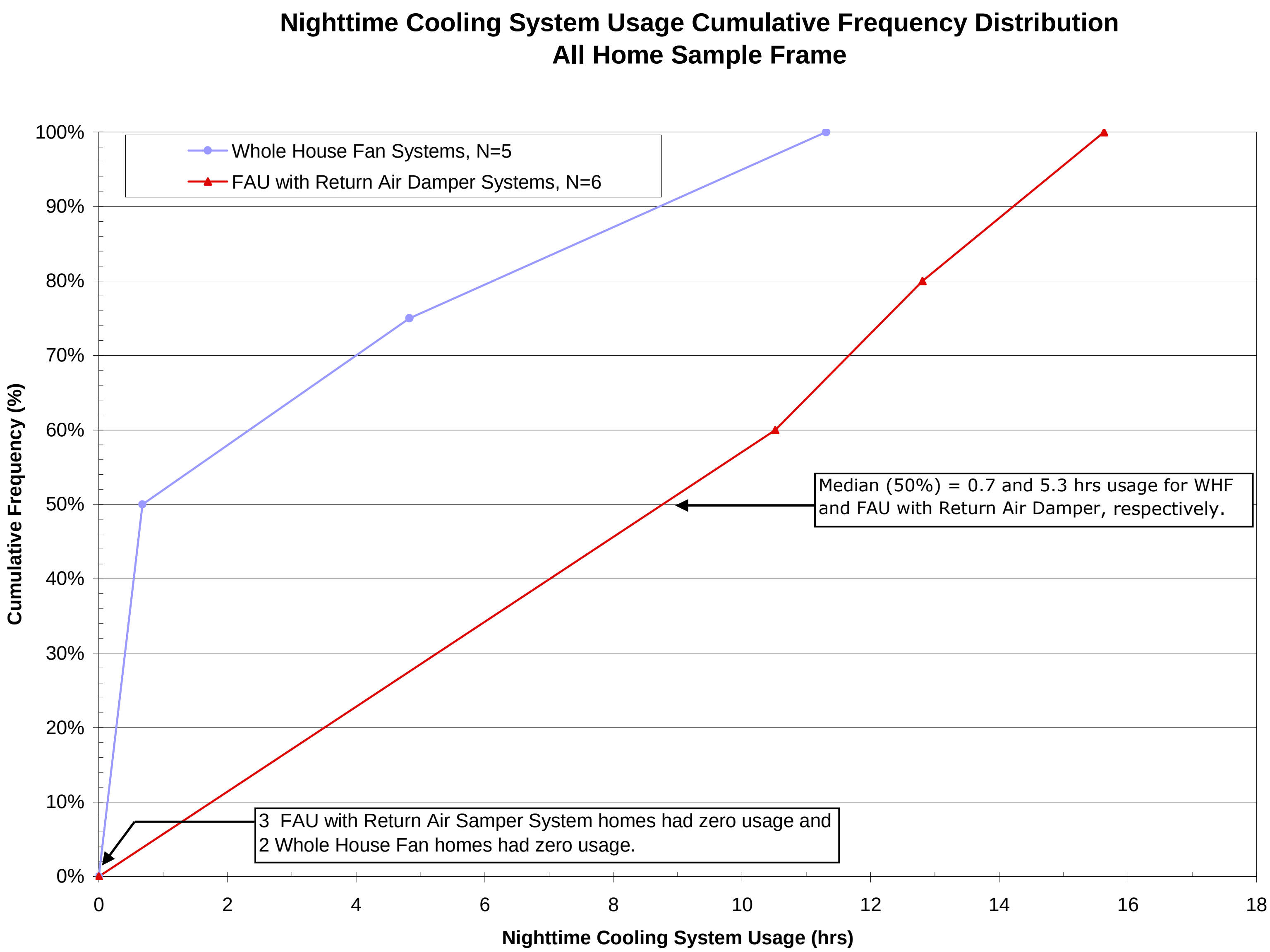


Figure 9. Nighttime cooling system usage cumulative frequency distribution – All Home Sample Frame.

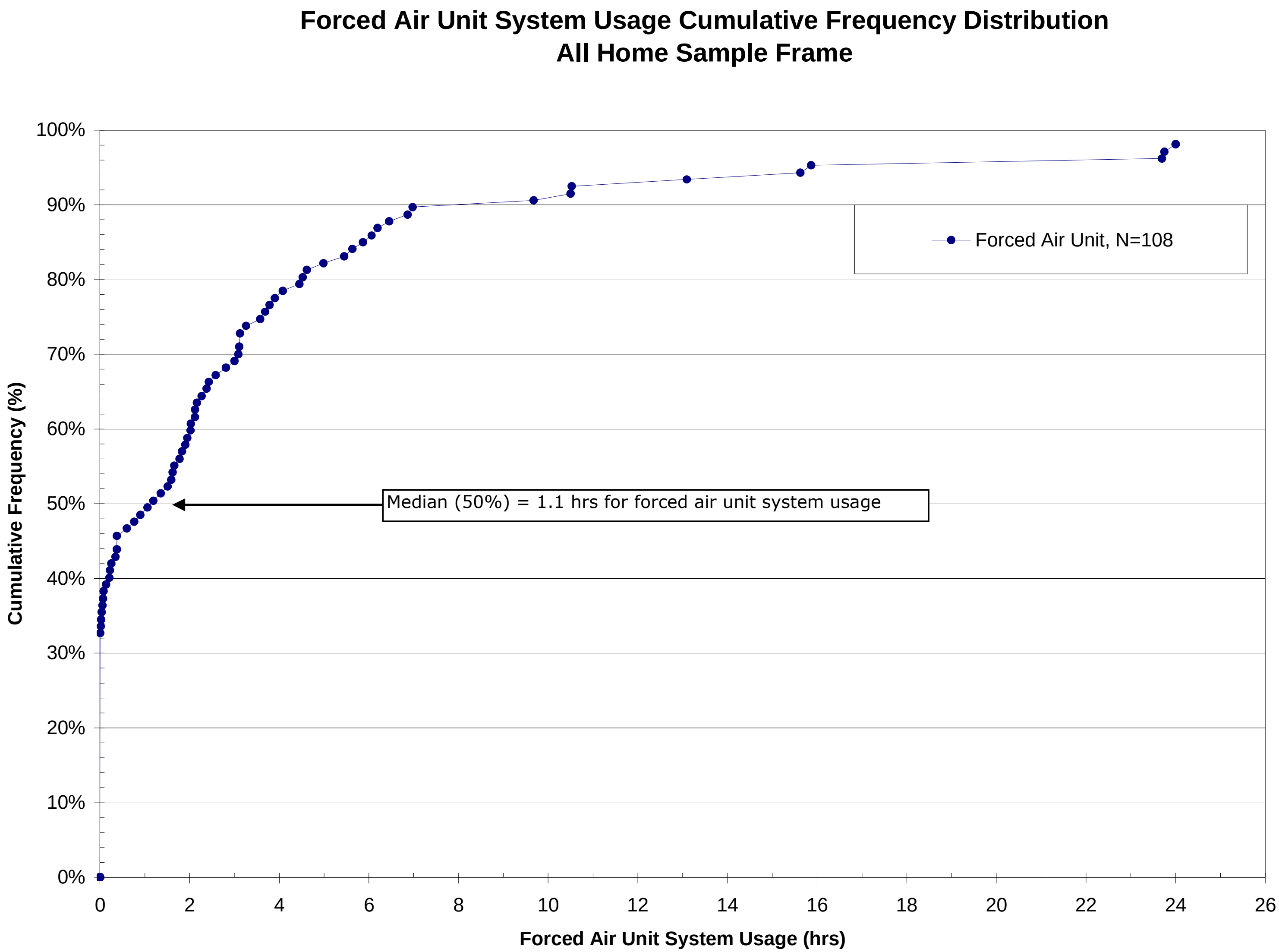


Figure 10. Forced air unit system usage – All Home Sample Frame.

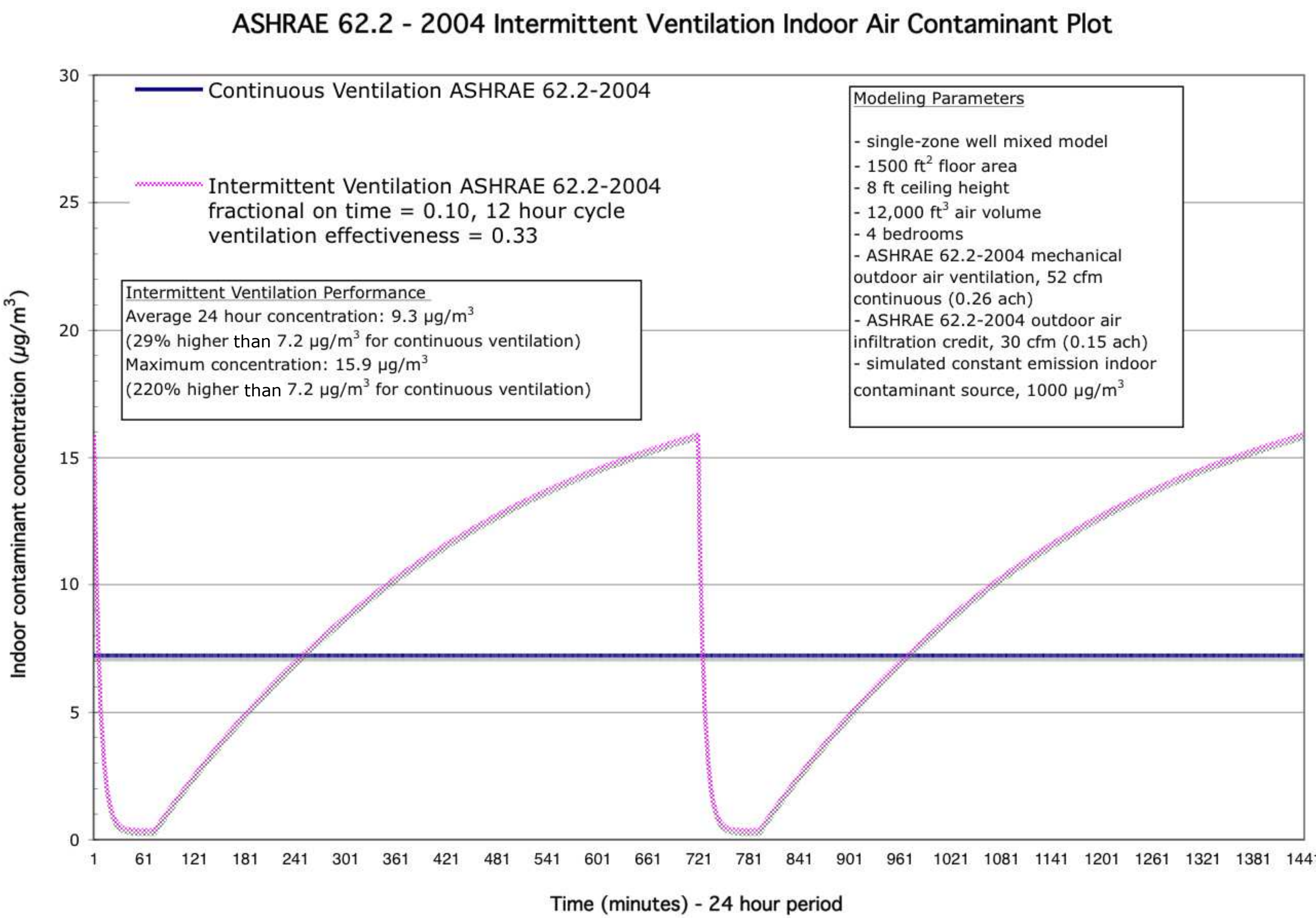


Figure 11. ASHRAE 62.2-2004 Intermittent ventilation indoor air contaminant concentration plot.

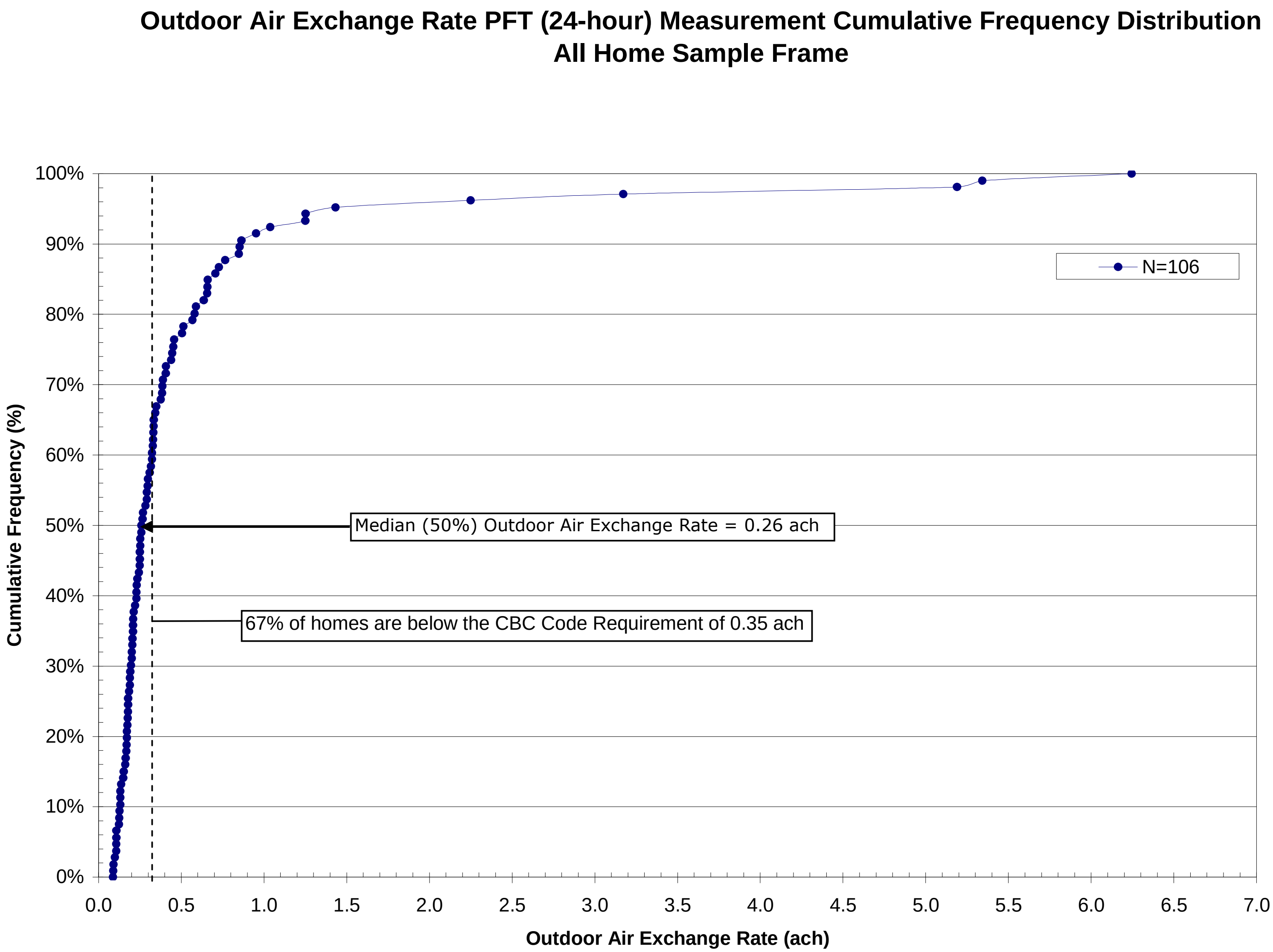


Figure 12. Outdoor air exchange rate PFT (24-hour) measurement cumulative frequency – All Home Sample Frame.

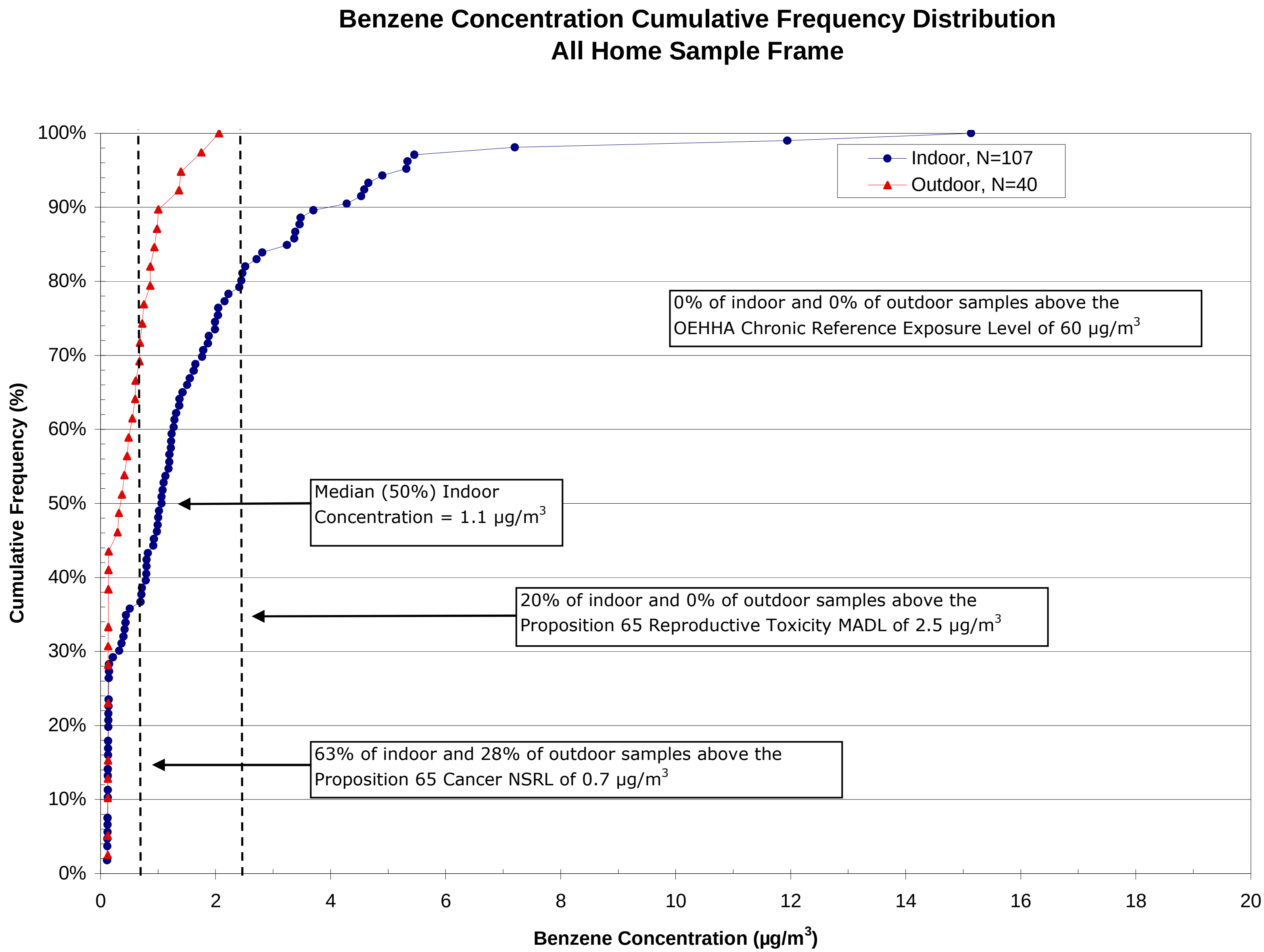


Figure 13. Benzene concentration cumulative frequency distribution – All Home Sample Frame.

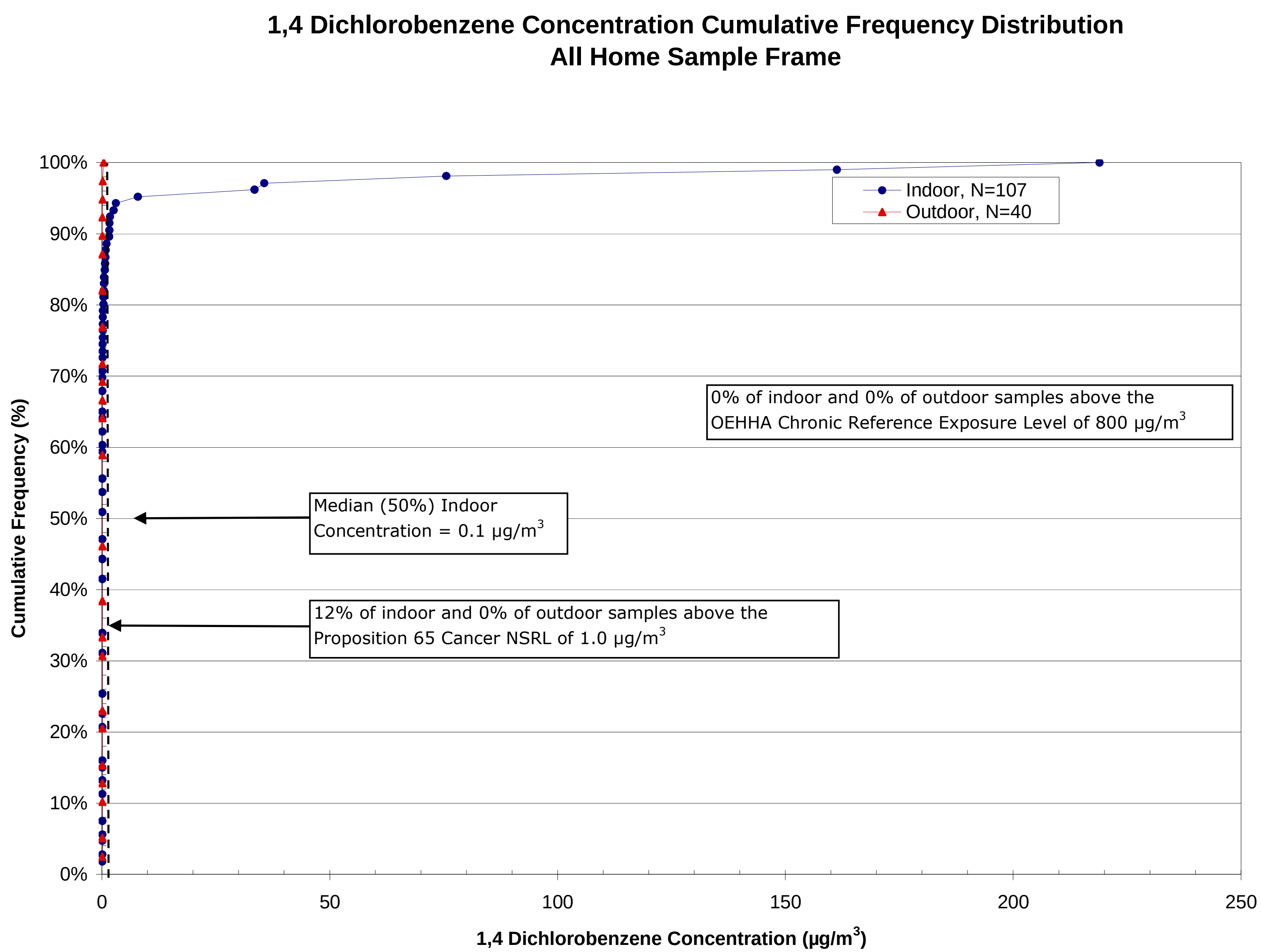


Figure 14. 1,4 Dichlorobenzene concentration cumulative frequency distribution –All Home Sample Frame.

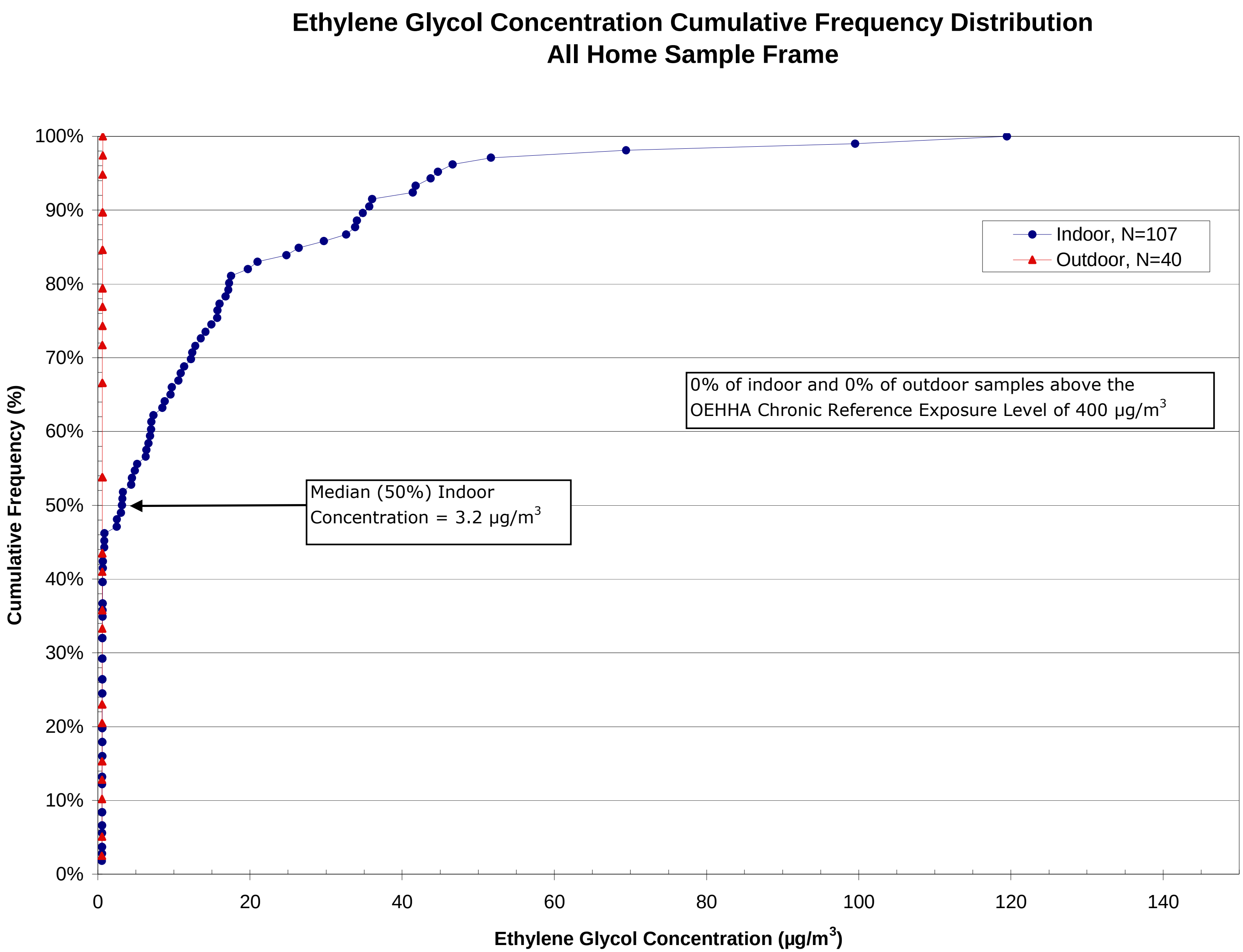


Figure 15. Ethylene glycol concentration cumulative frequency distribution – All Home Sample Frame.

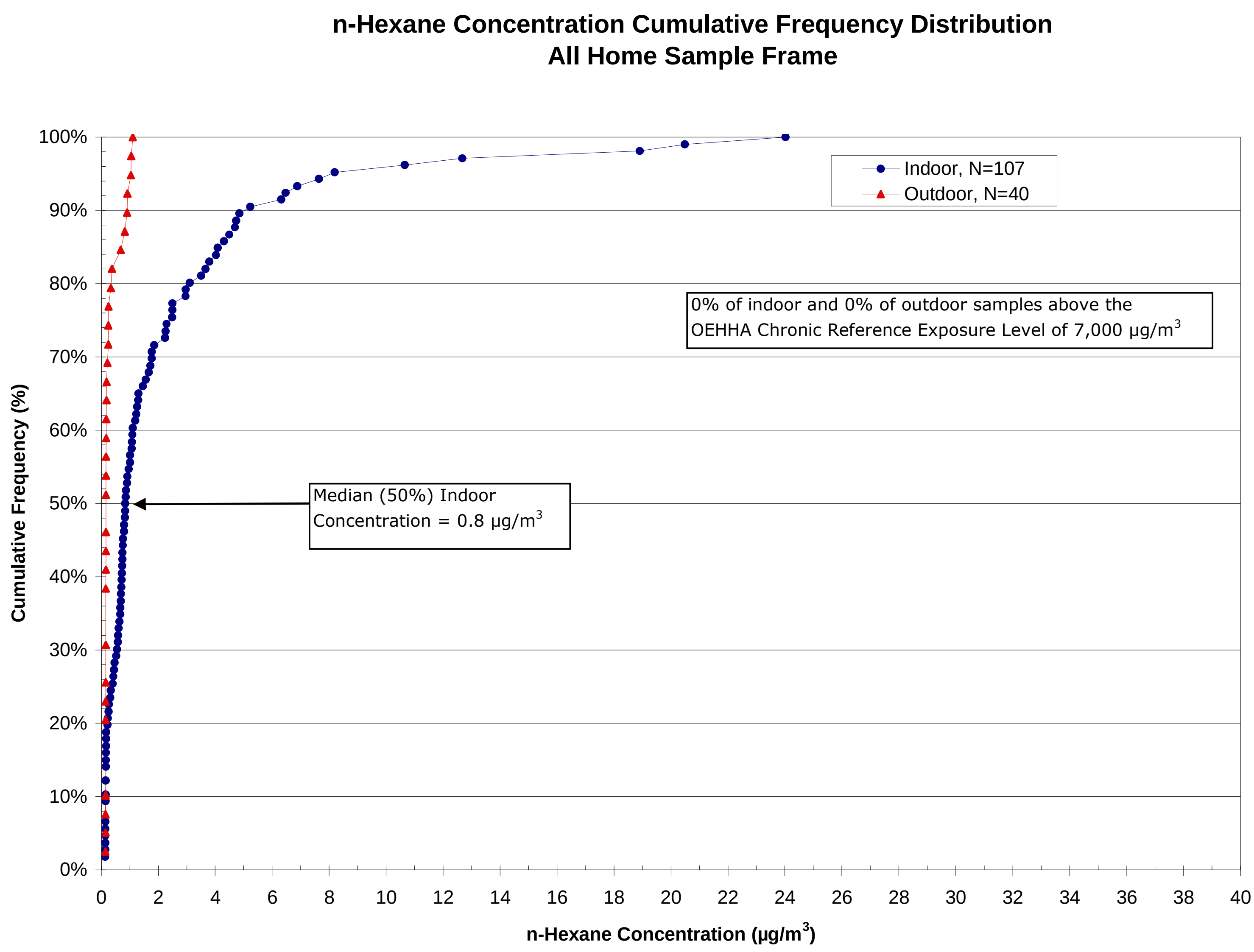


Figure 16. n-Hexane concentration cumulative frequency distribution – All Home Sample Frame.

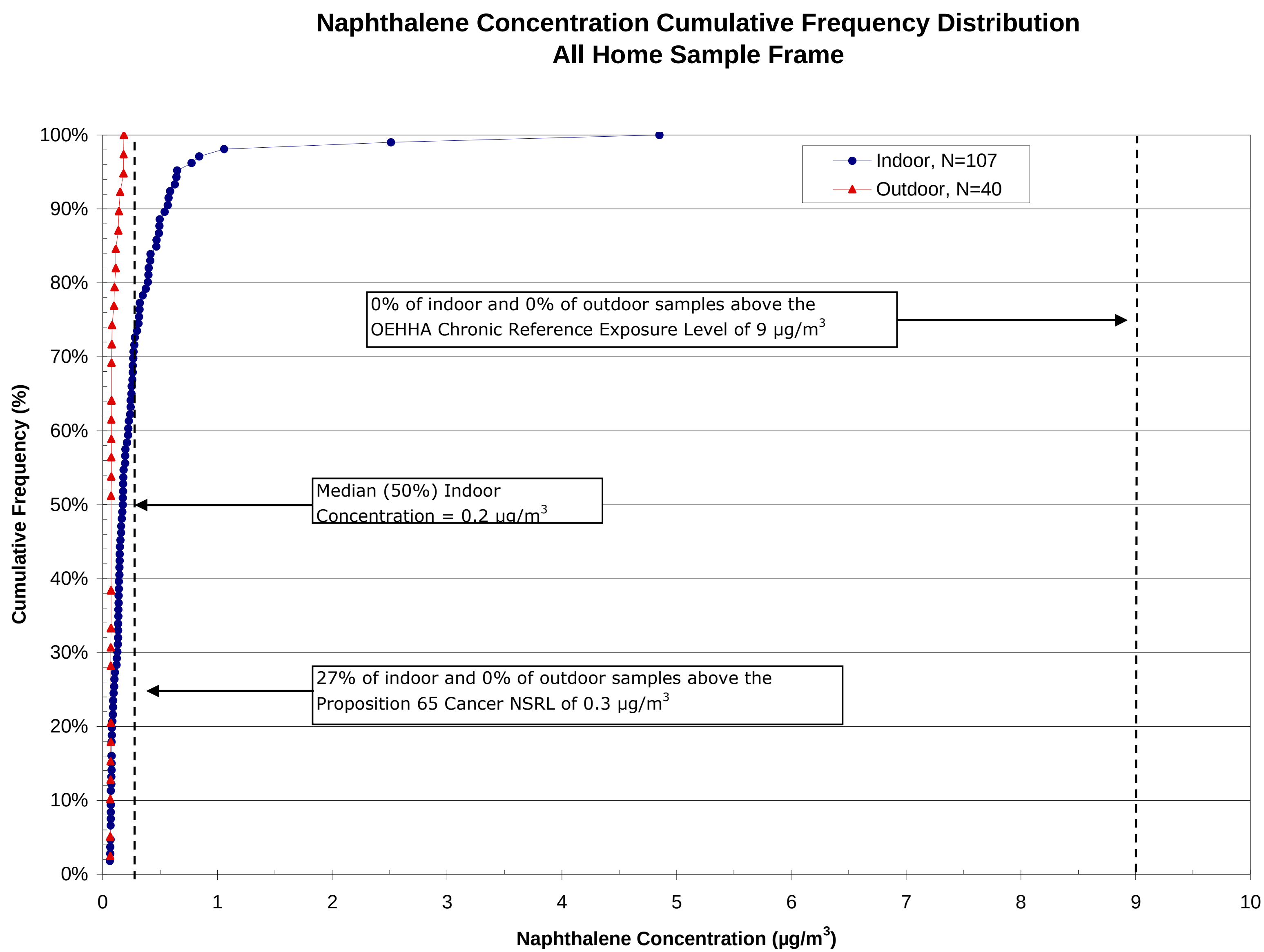


Figure 17. Naphthalene concentration cumulative frequency distribution – All Home Sample Frame.

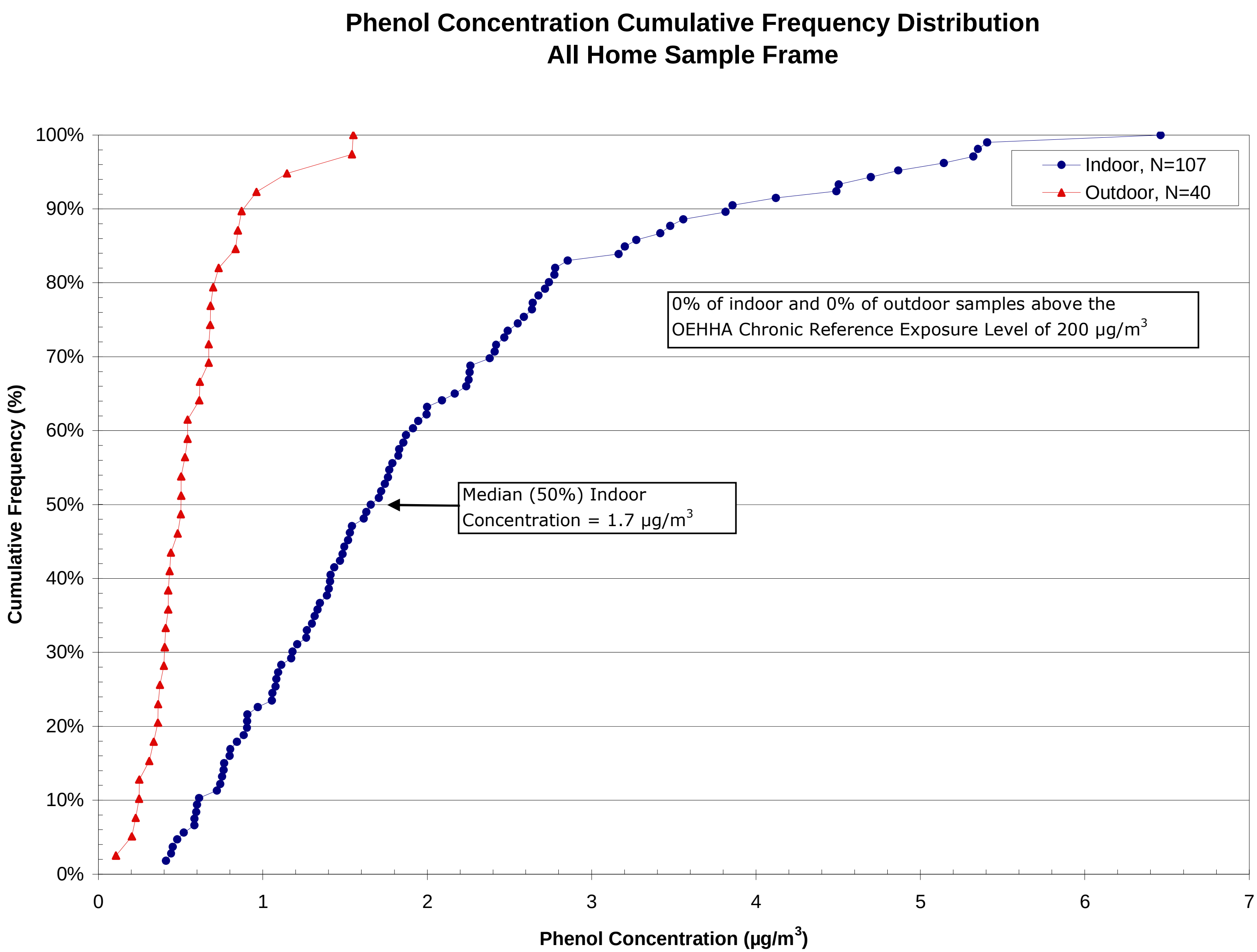


Figure 18. Phenol concentration cumulative frequency distribution – All Home Sample Frame.

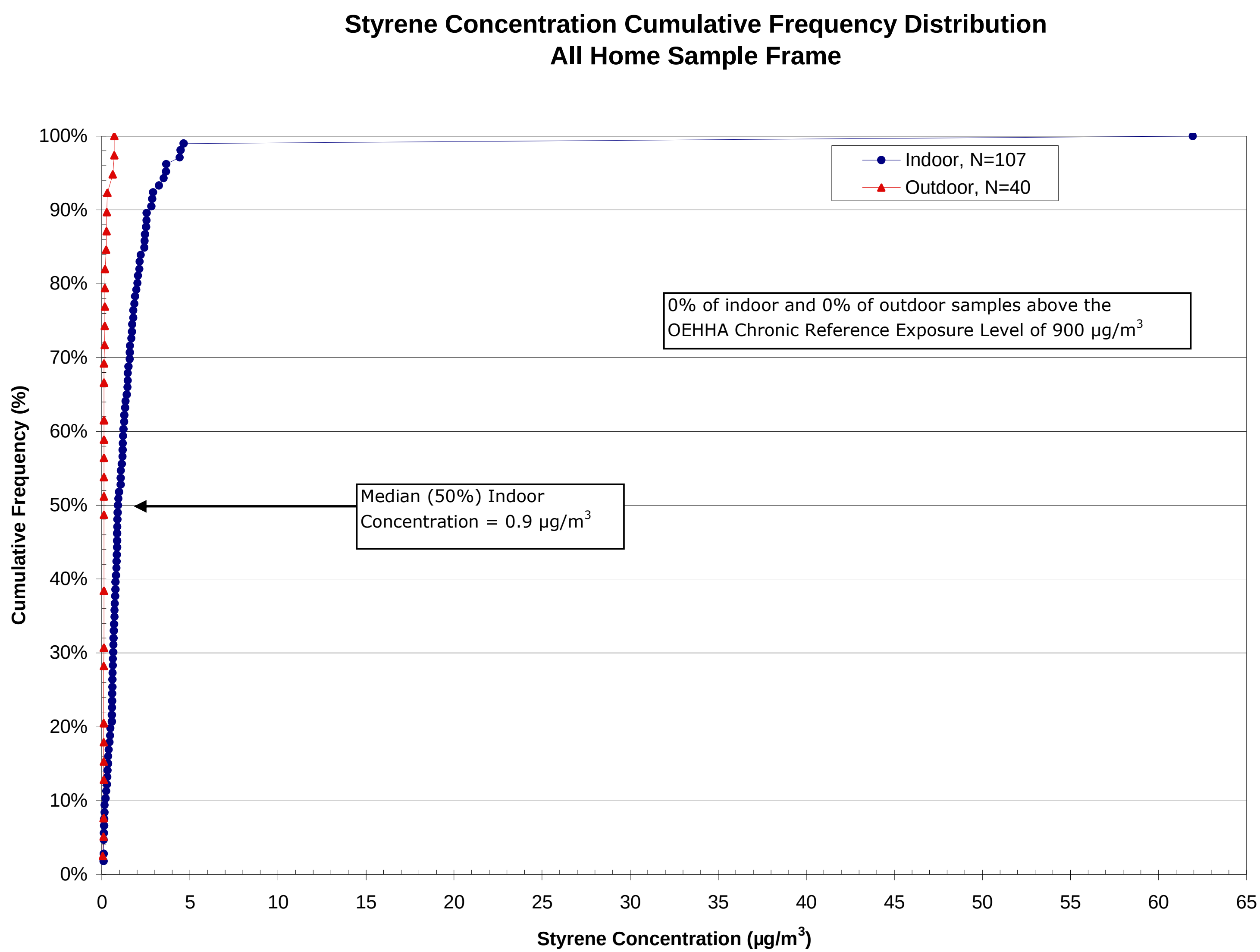


Figure 19. Styrene concentration cumulative frequency distribution – All Home Sample Frame.

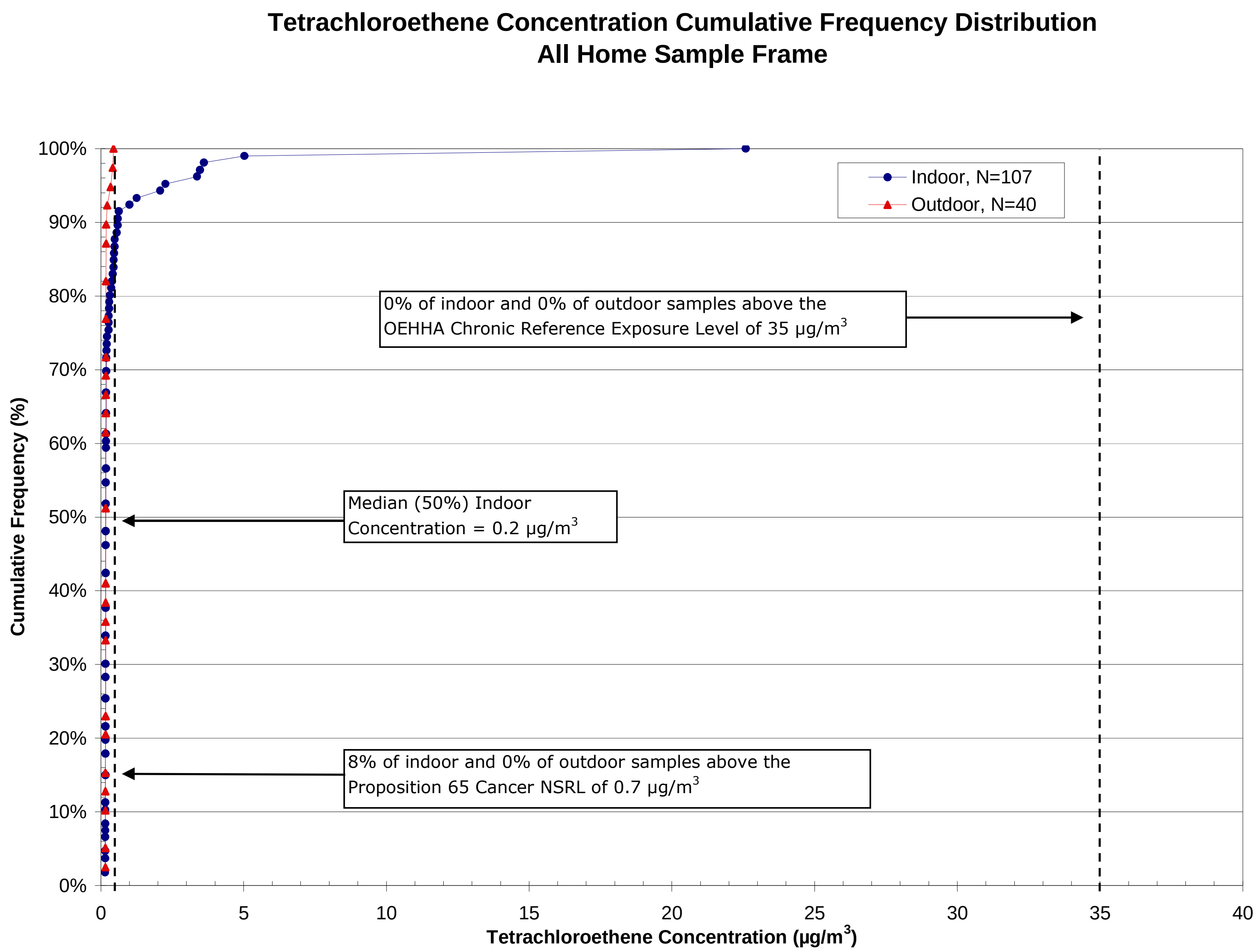


Figure 20. Tetrachloroethene concentration cumulative frequency distribution – All Home Sample Frame.

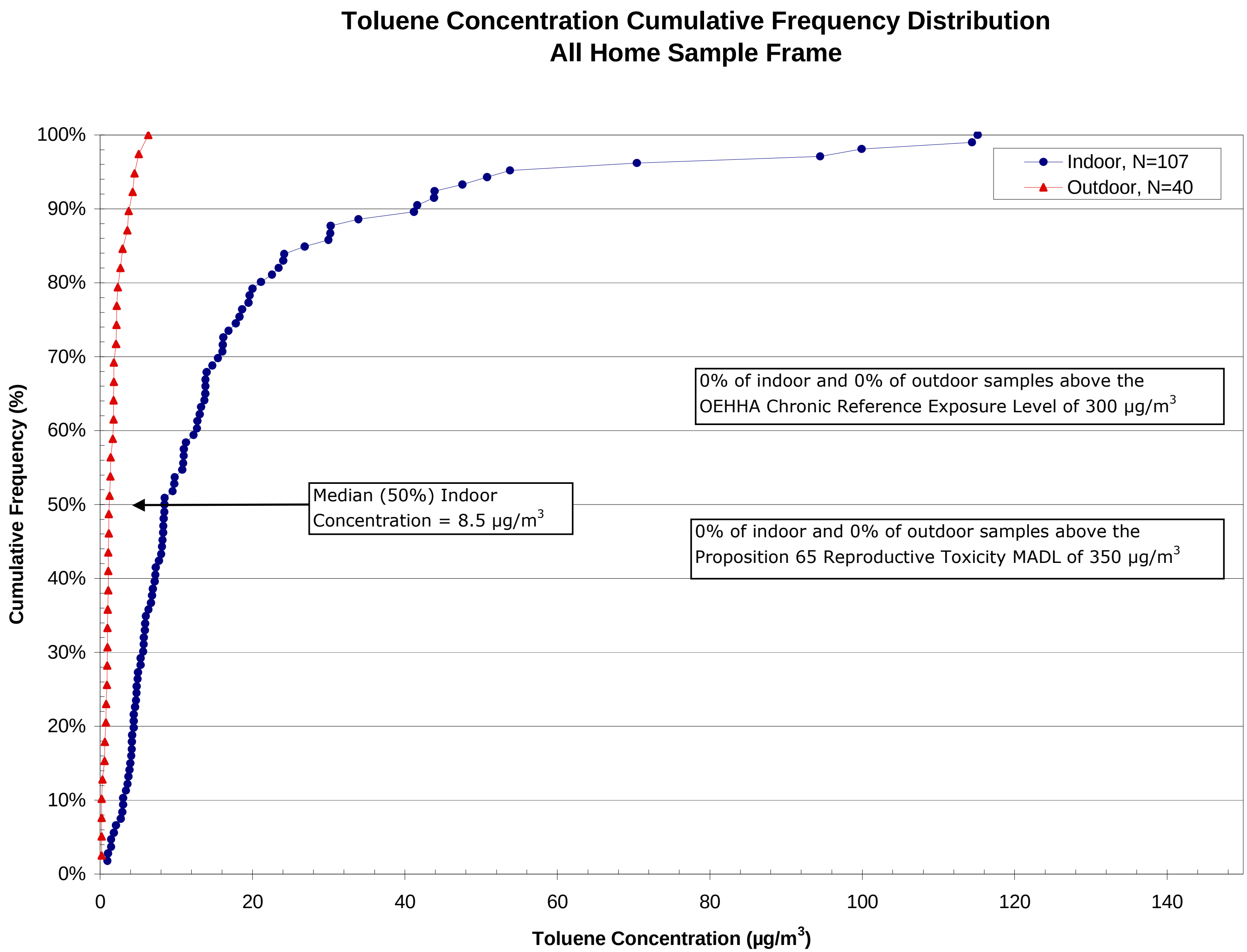


Figure 21. Toluene concentration cumulative frequency distribution – All Home Sample Frame.

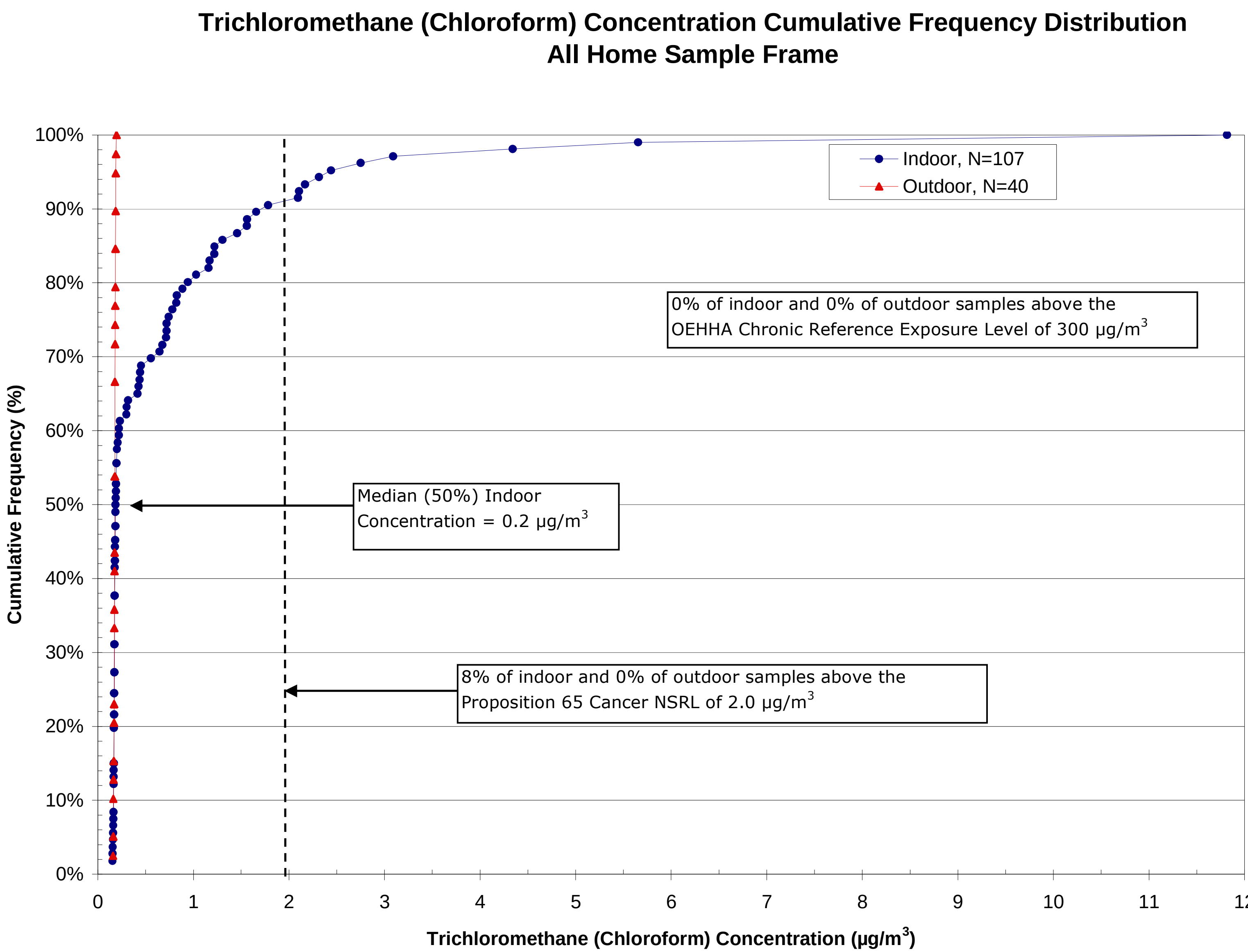


Figure 22. Trichloromethane (chloroform) cumulative frequency distribution – All Home Sample Frame.

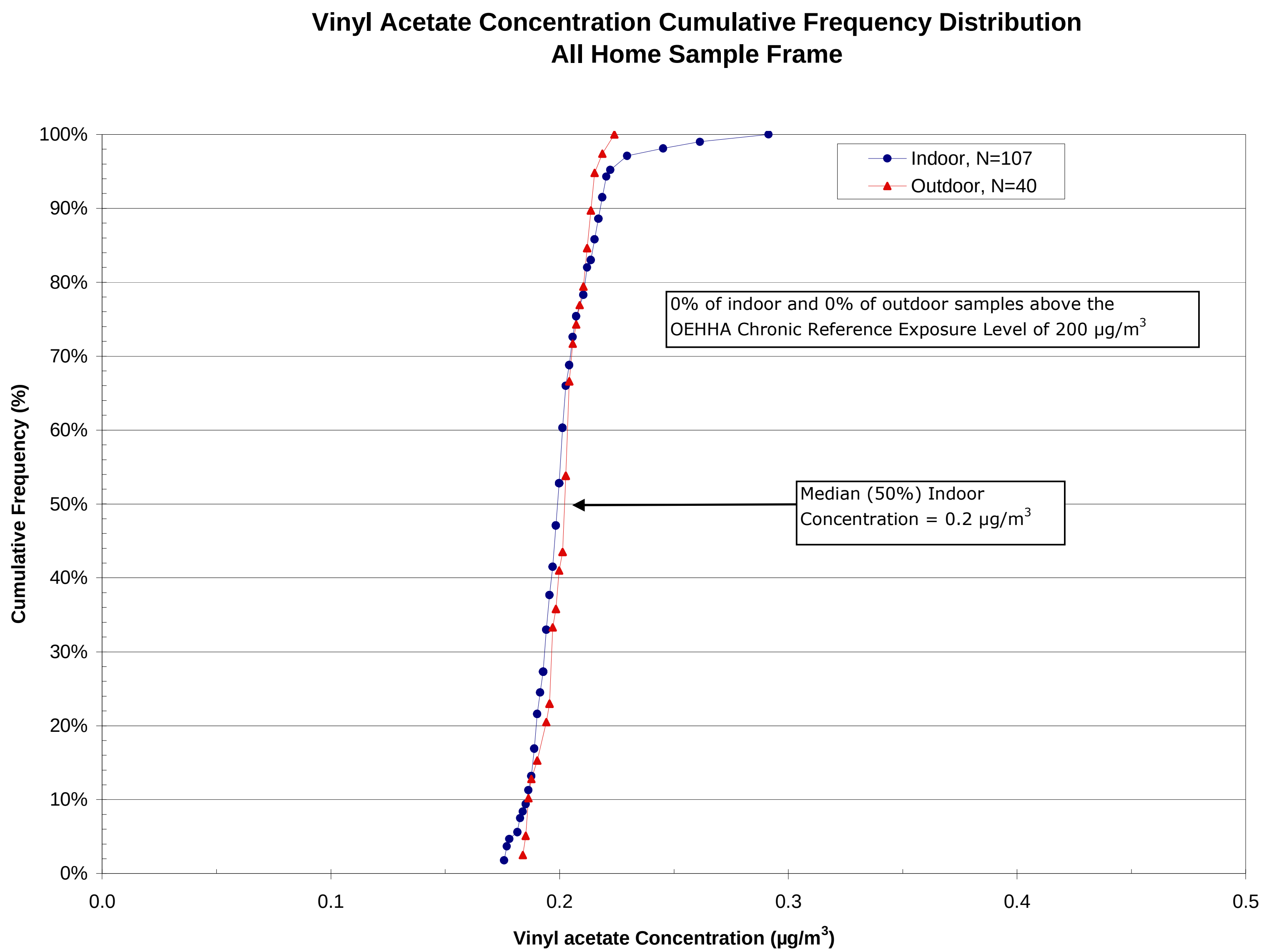


Figure 23. Vinyl acetate concentration cumulative frequency distribution – All Home Sample Frame.

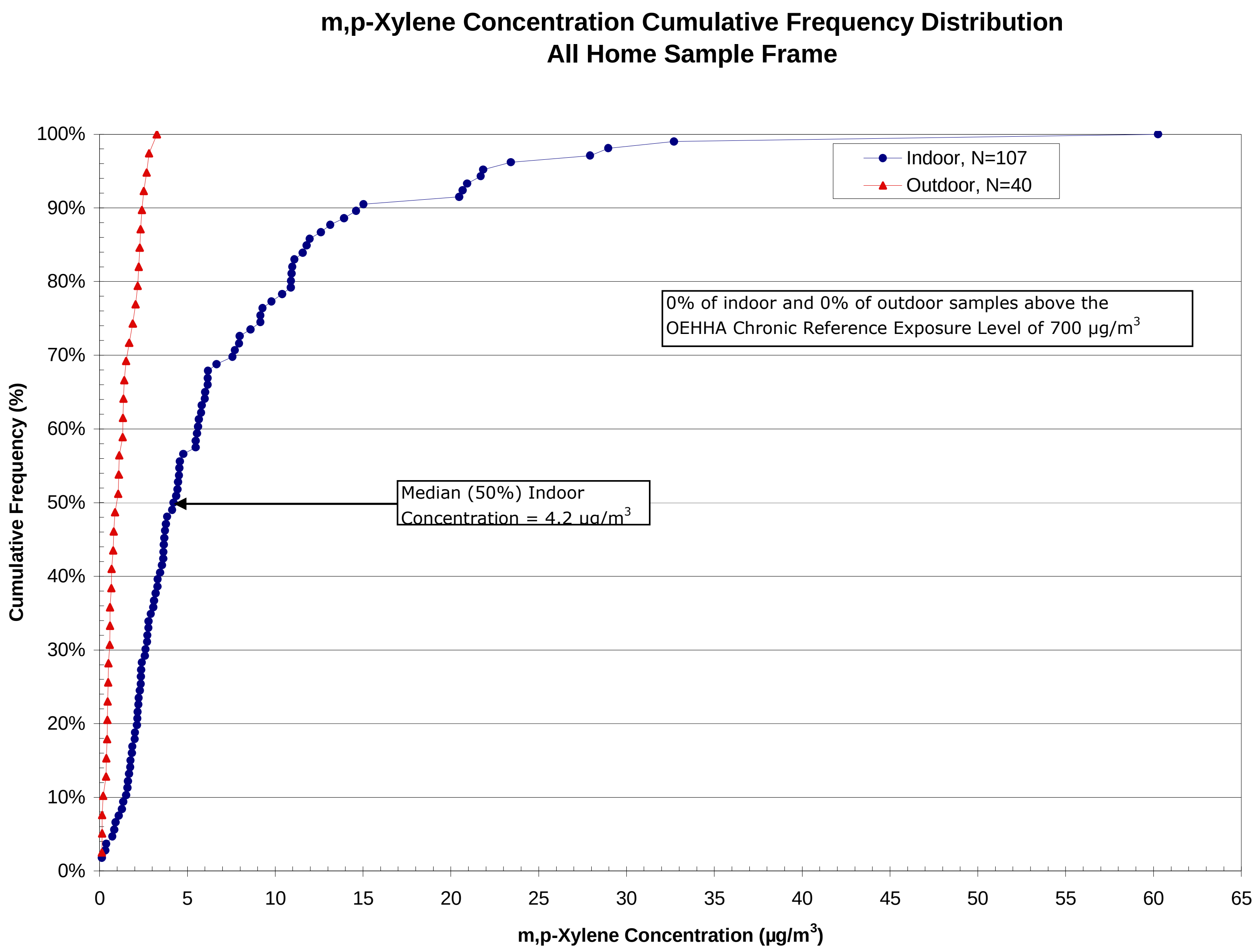


Figure 24. m,p-Xylene concentration cumulative frequency distribution – All Home Sample Frame.

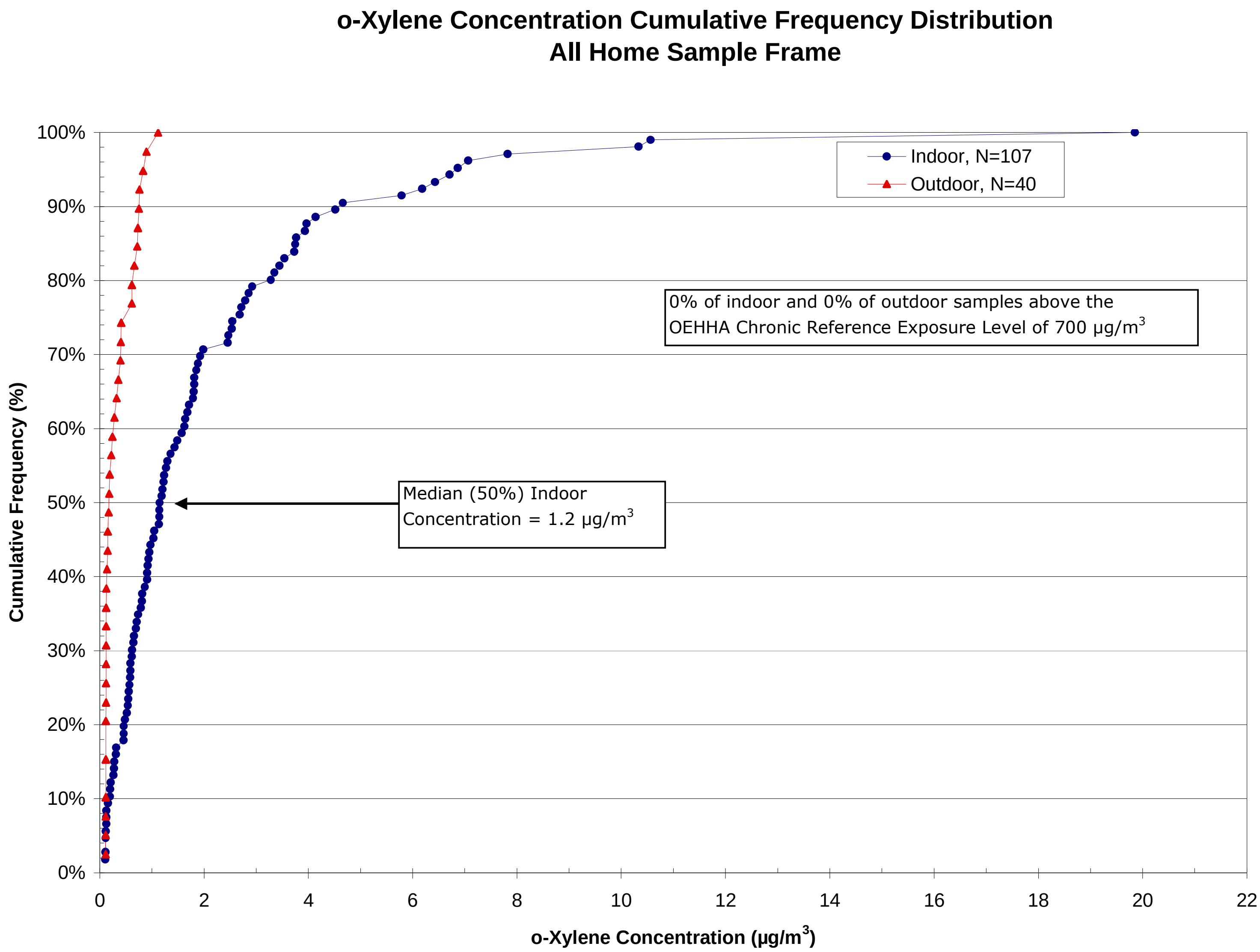


Figure 25. o-Xylene concentration cumulative frequency distribution – All Home Sample Frame.

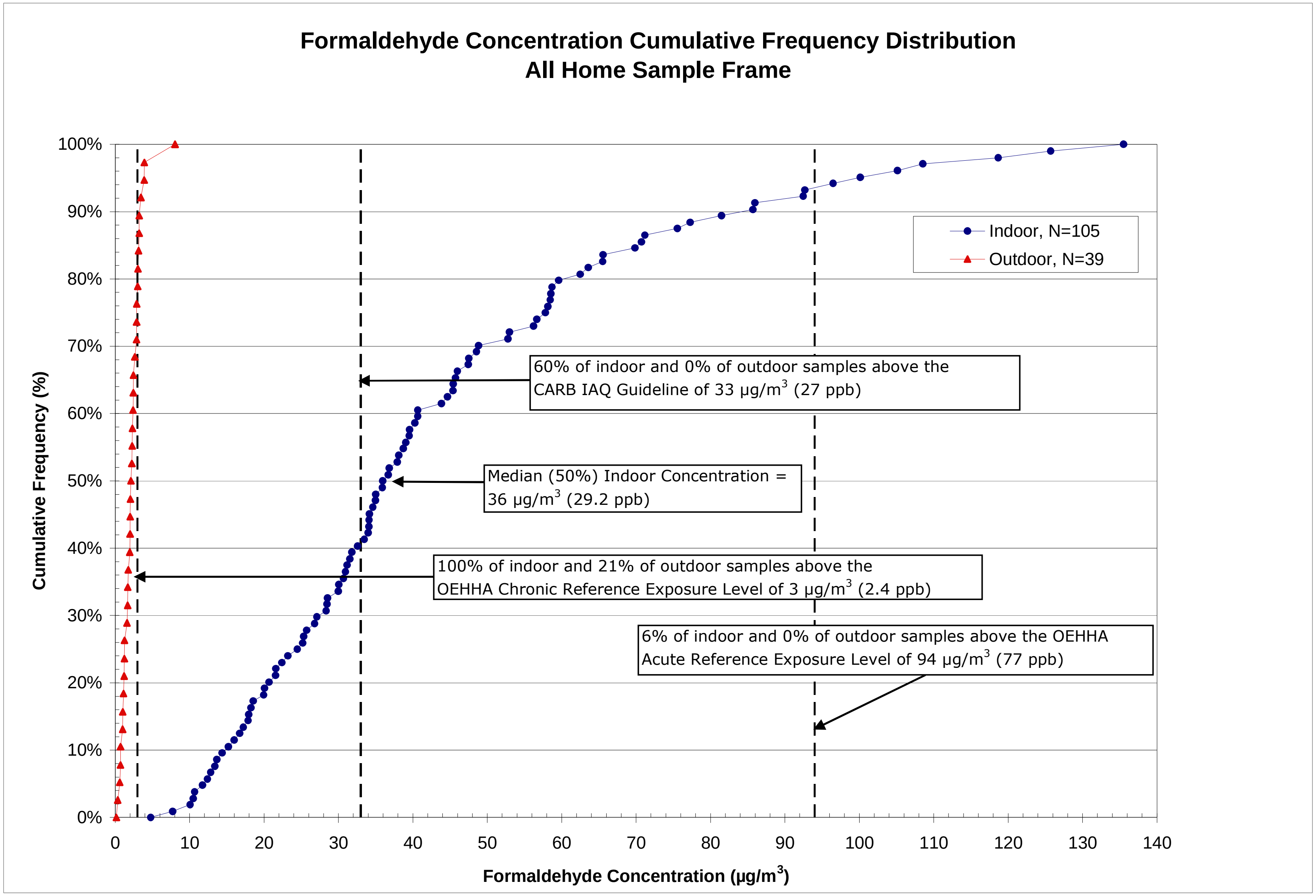


Figure 26. Formaldehyde concentration cumulative frequency distribution – All Home Sample Frame.

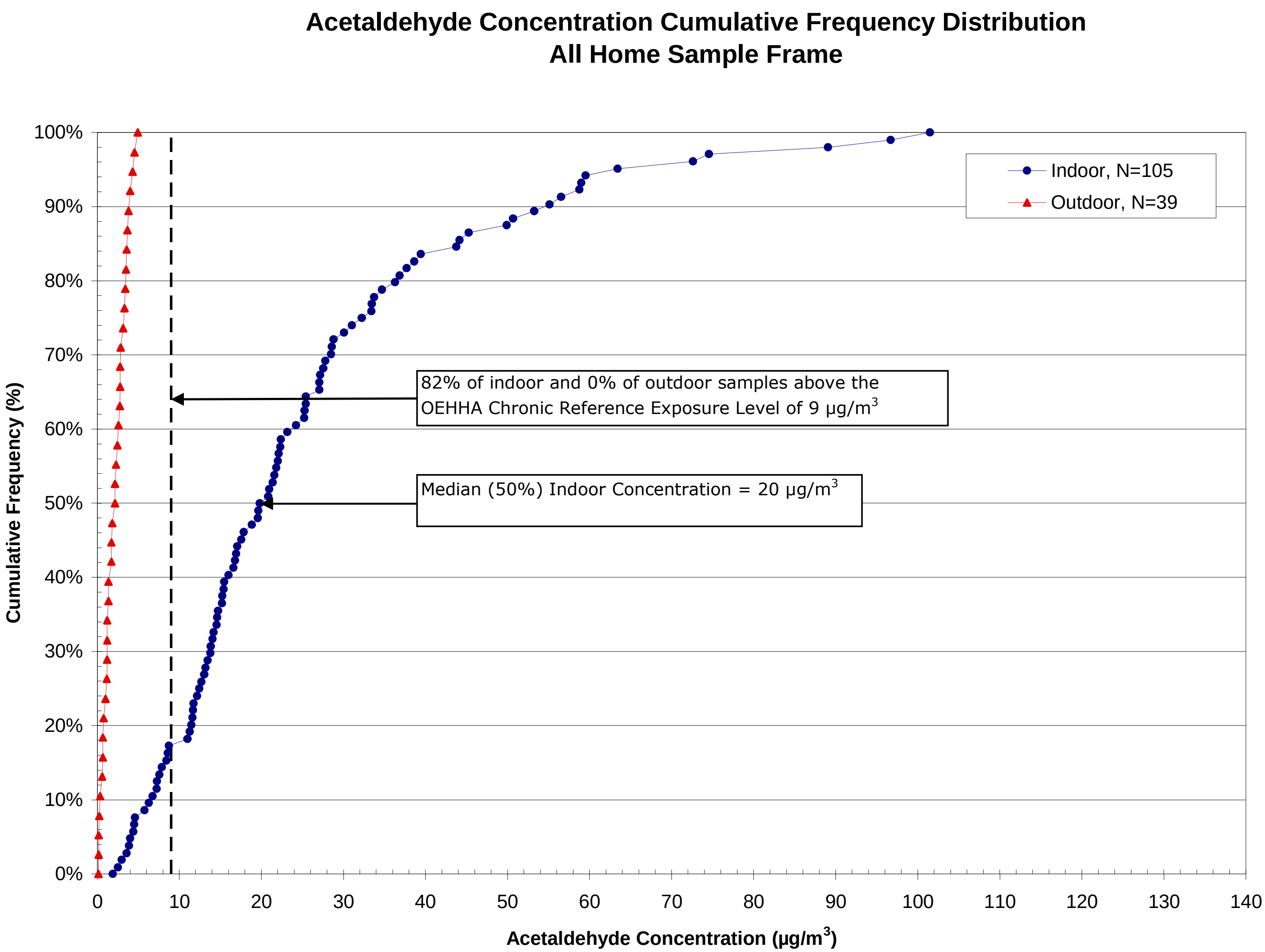


Figure 27. Acetaldehyde concentration frequency distribution – All Home Sample Frame.

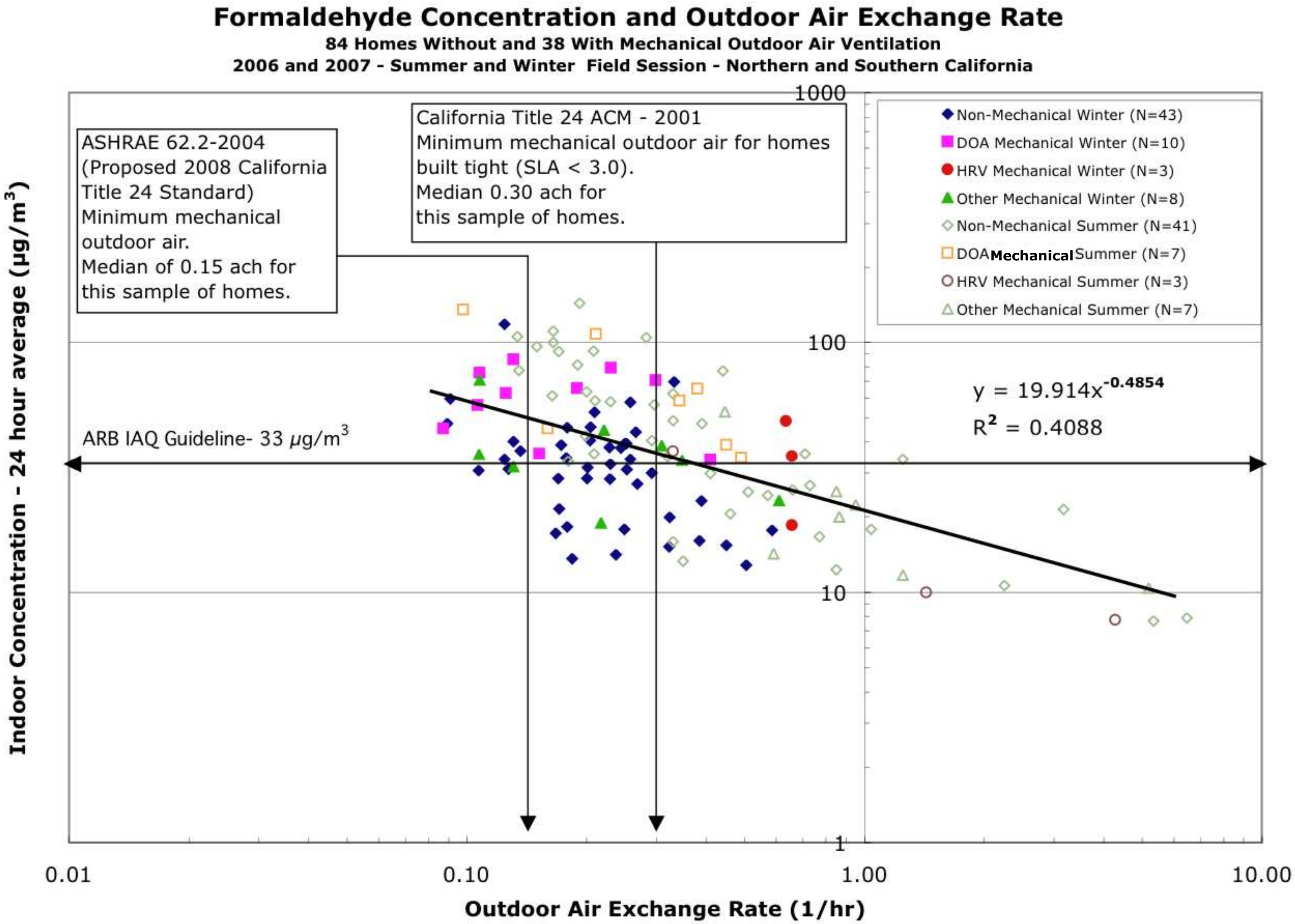


Figure 28. Formaldehyde indoor concentrations and outdoor air exchange rates.

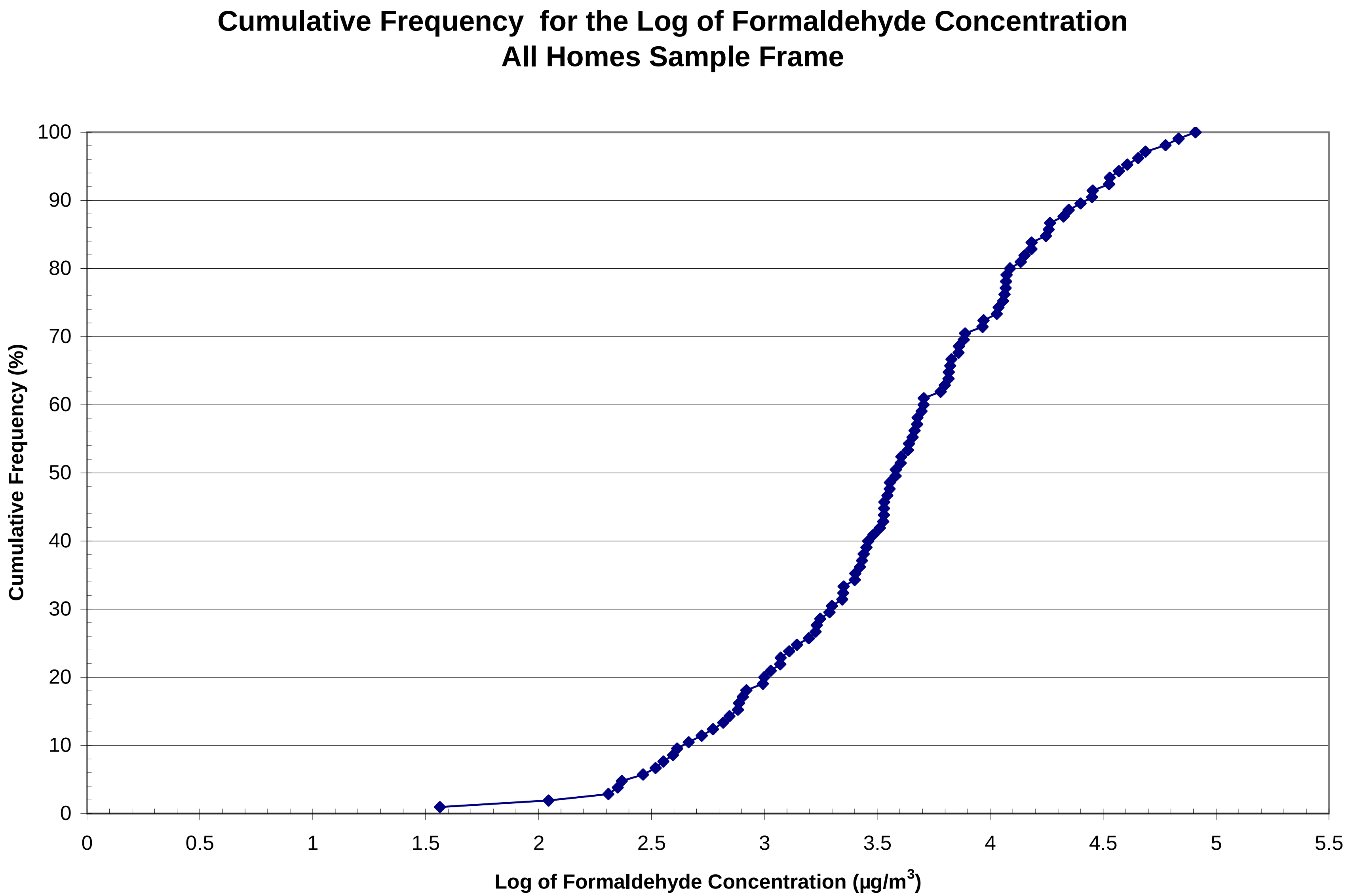


Figure 29. Cumulative frequency distribution of the log of formaldehyde concentration – All Homes Sample Frame.

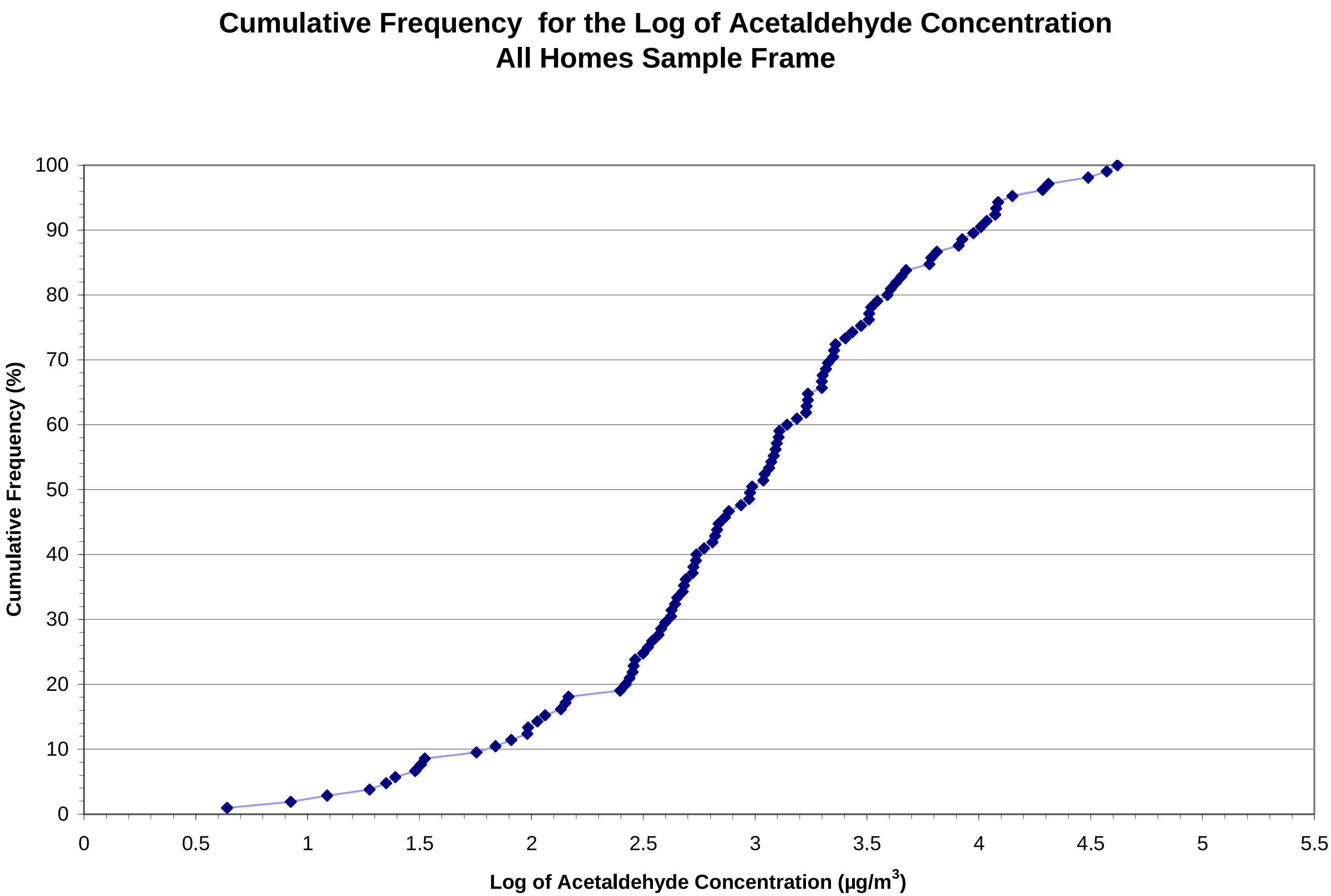


Figure 30. Cumulative frequency distribution of the log of acetaldehyde concentration – All Homes Sample Frame.

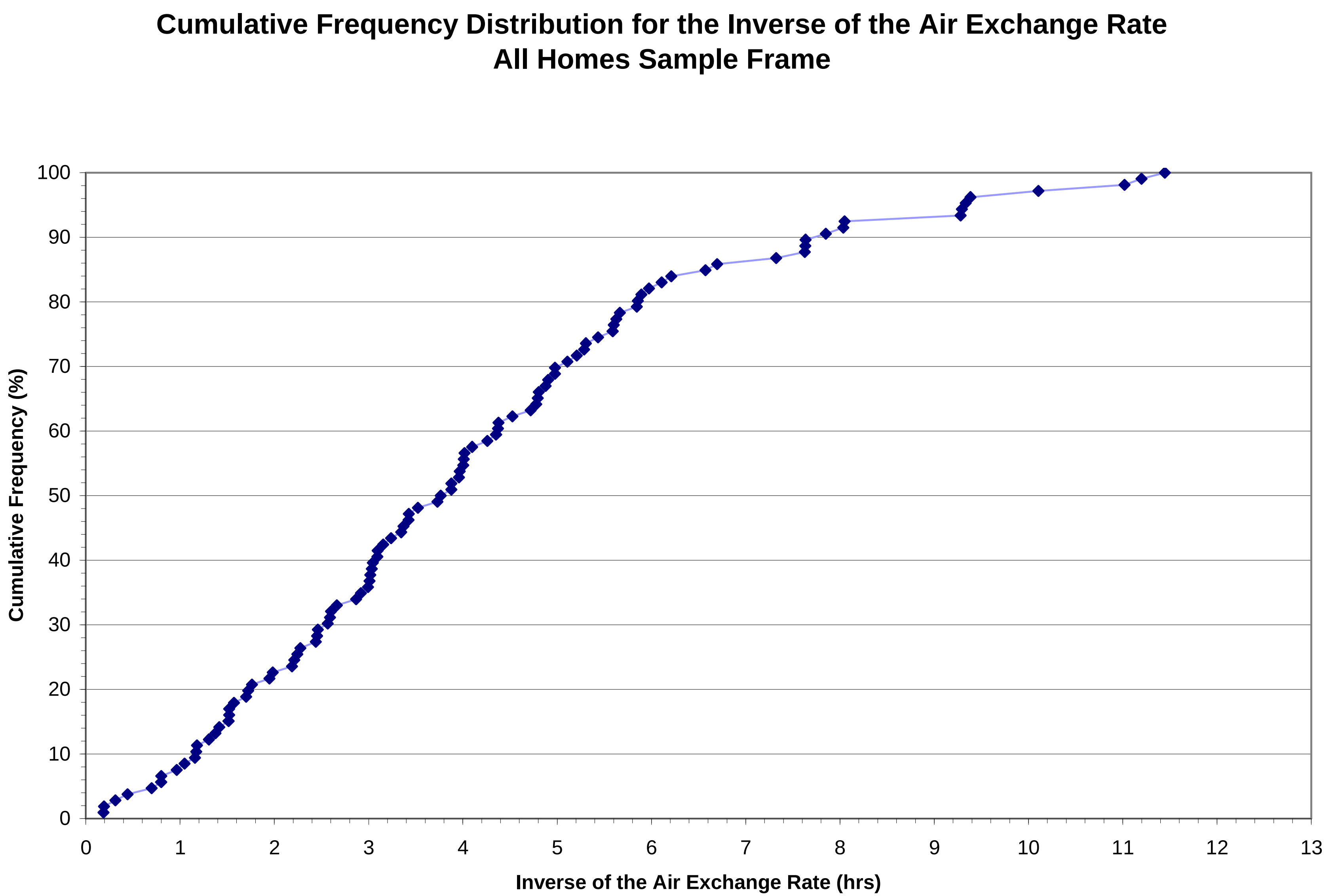


Figure 31. Cumulative frequency distribution for the inverse of the air exchange rate – All Homes Sample Frame.

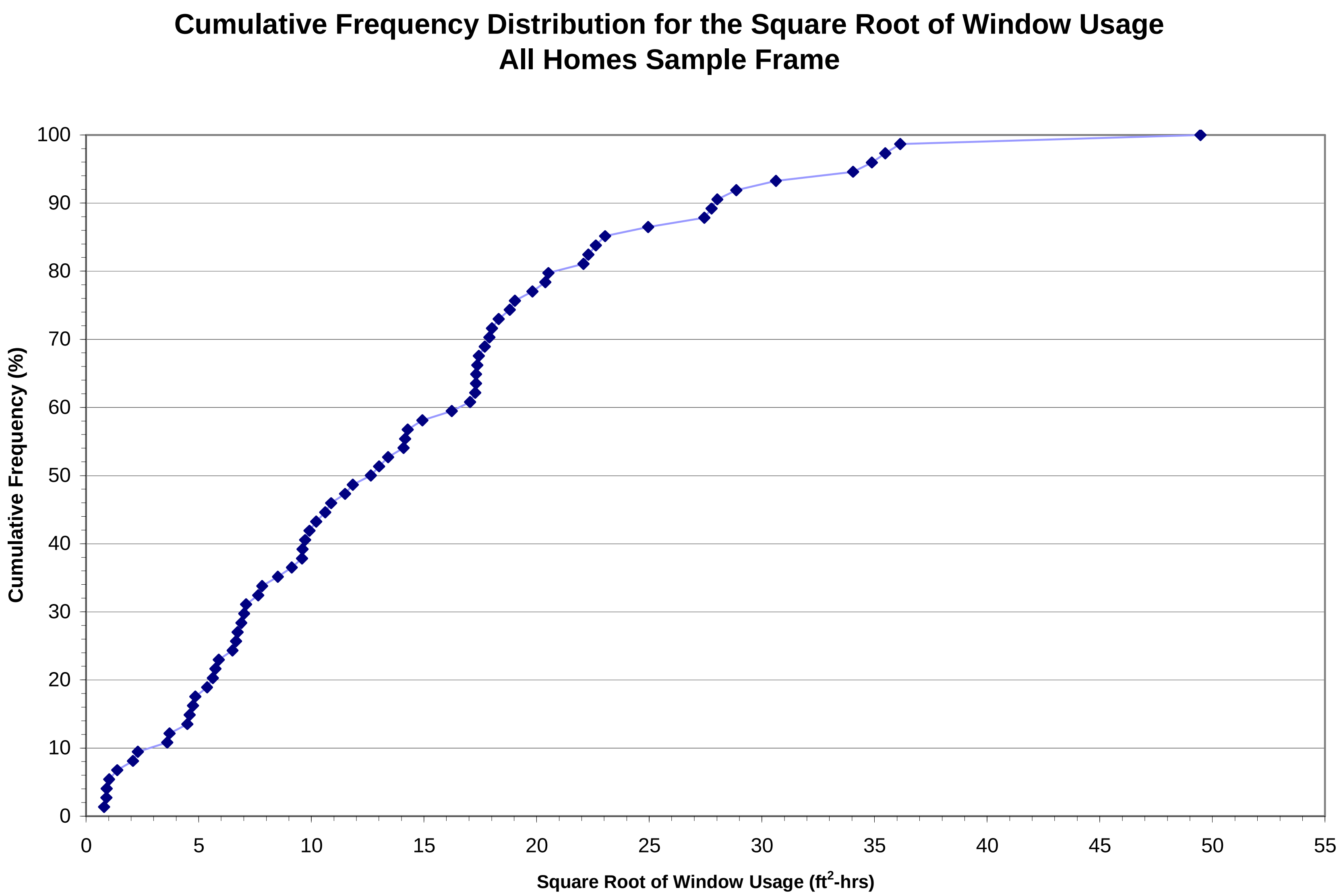


Figure 32. Cumulative frequency distribution of the square root of window usage – All Homes Sample Frame.

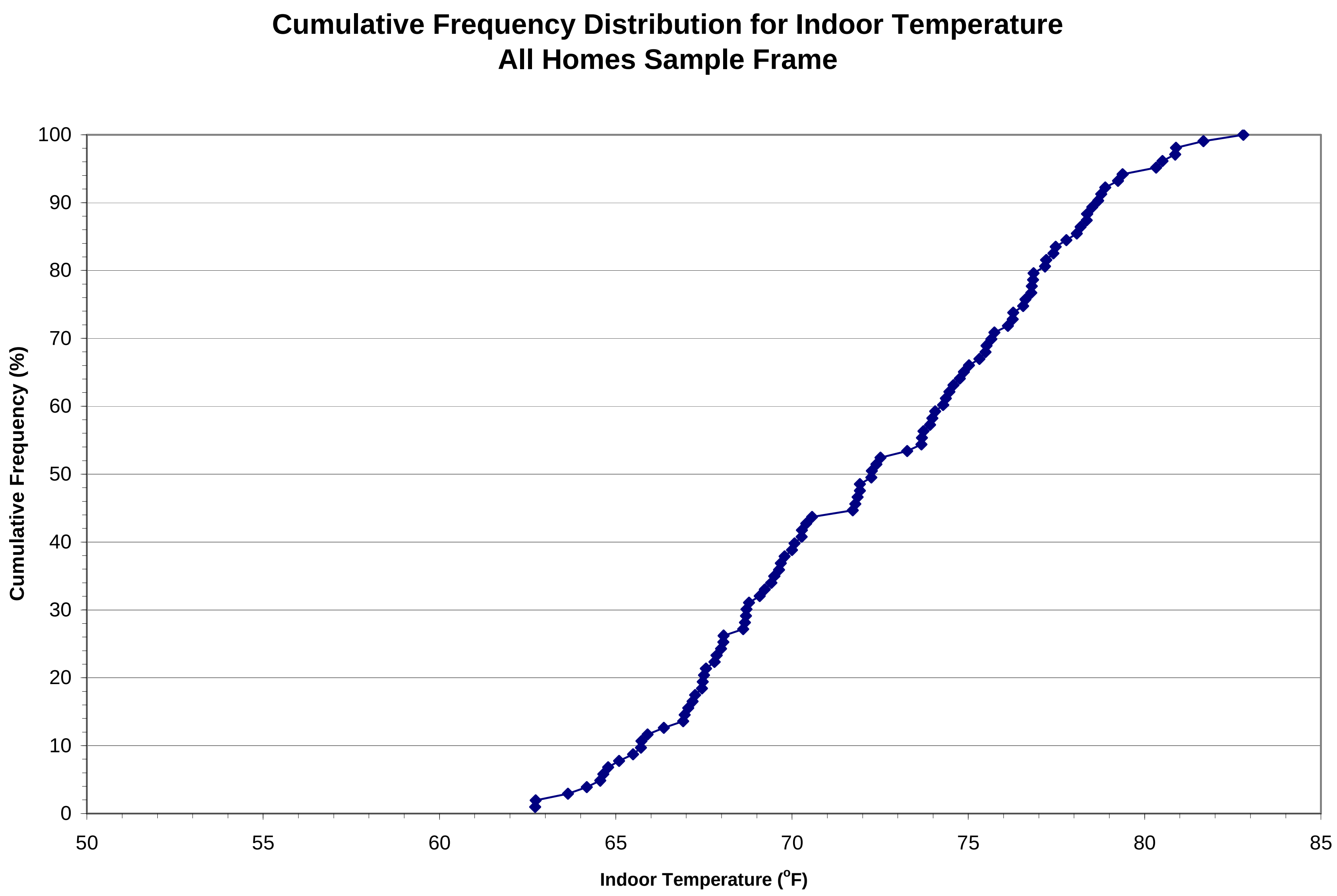


Figure 33. Cumulative frequency distribution for indoor temperature – All Homes Sample Frame.

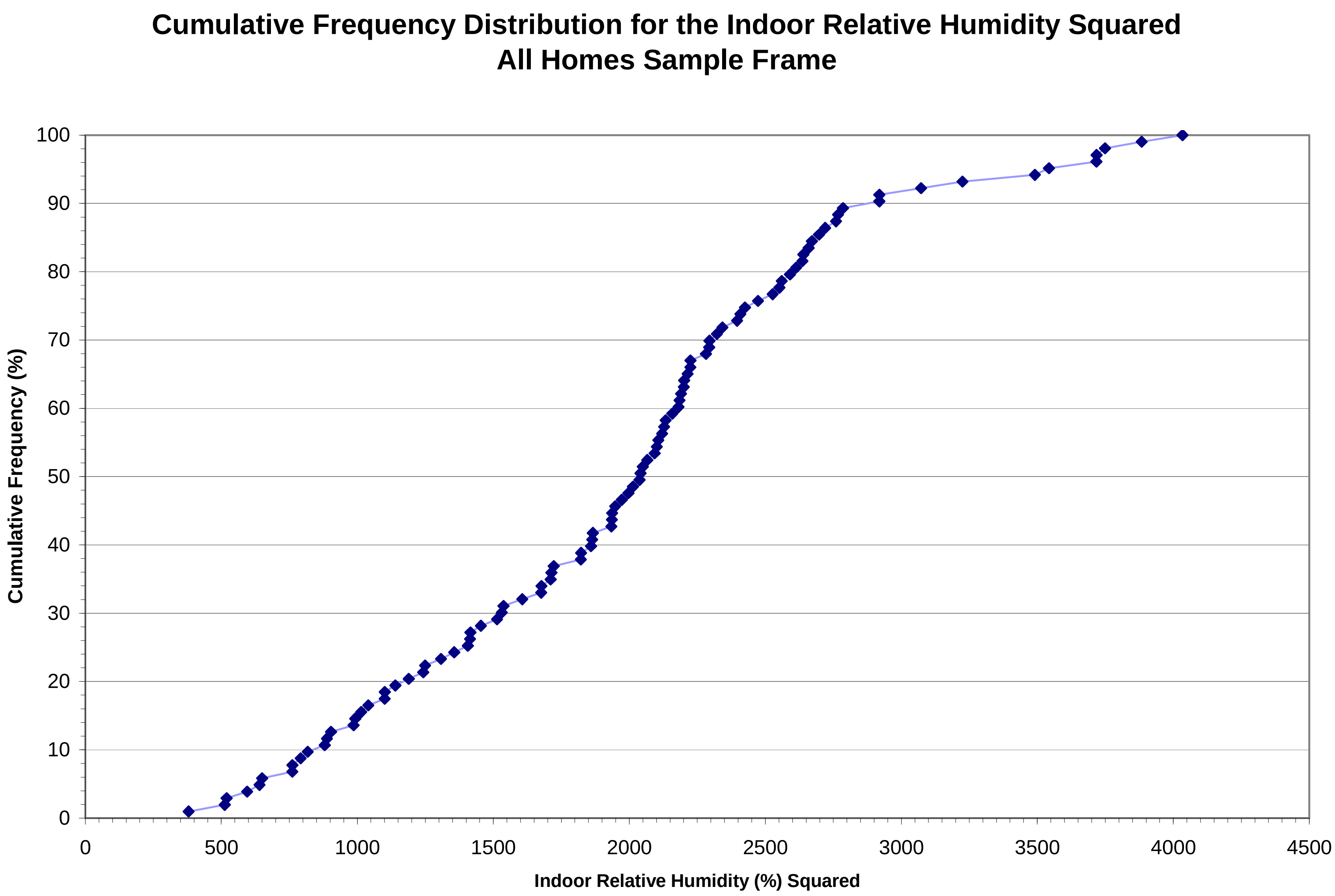


Figure 34. Cumulative frequency for the indoor relative humidity squared – All Homes Sample Frame.

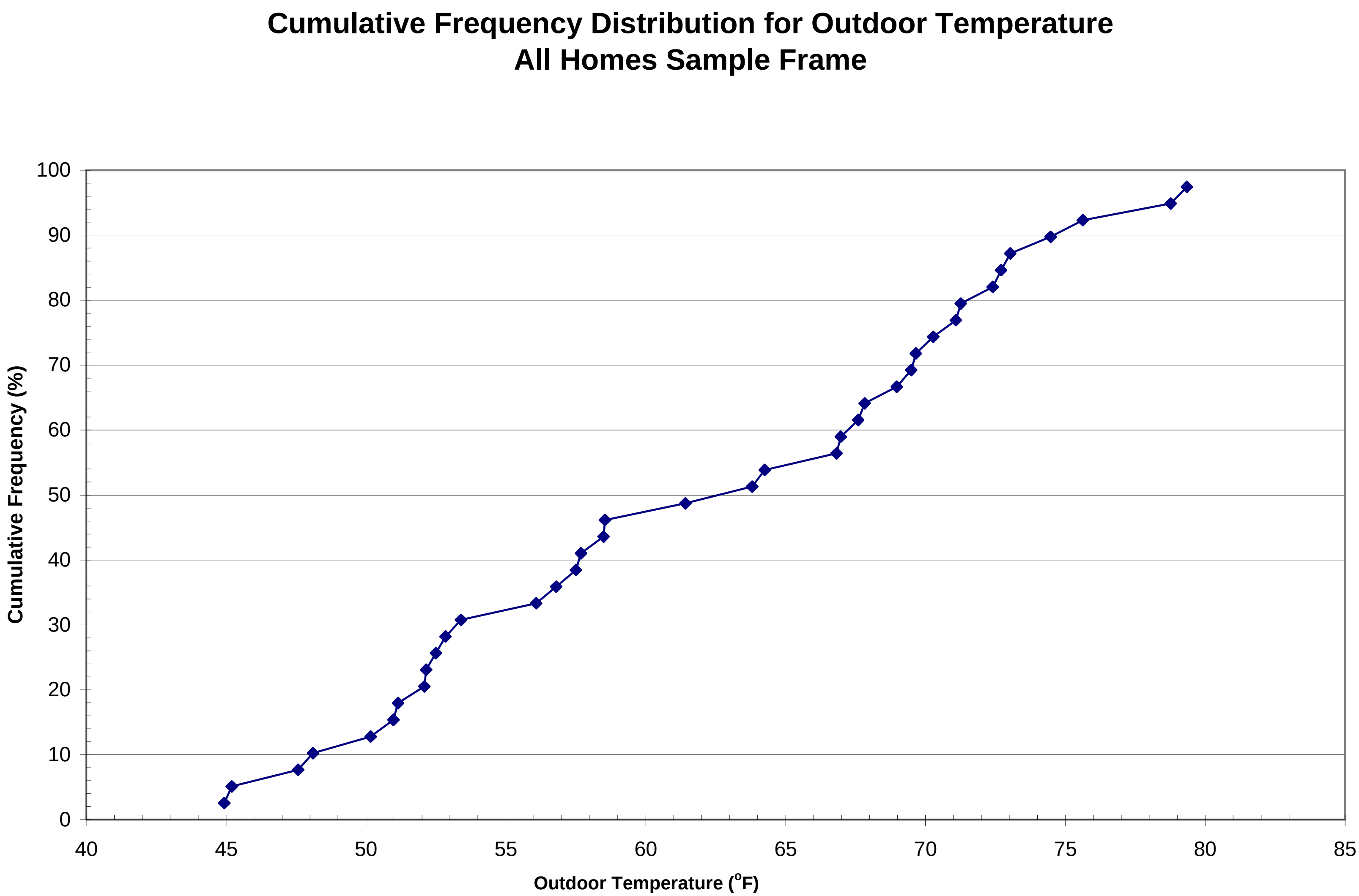


Figure 35. Cumulative frequency distribution for outdoor temperature – All Homes Sample Frame.

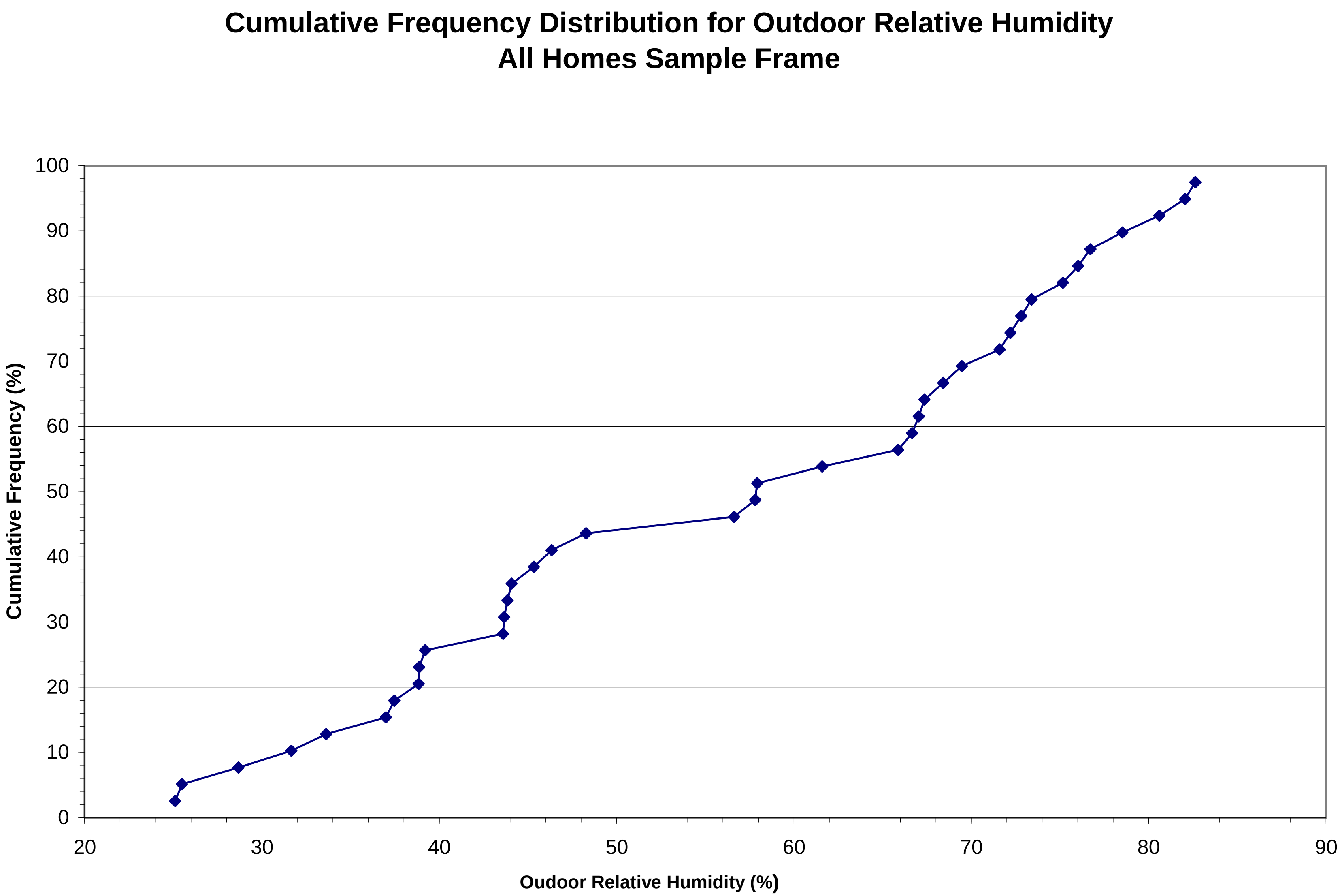


Figure 36. Cumulative frequency distribution for outdoor relative humidity – All Homes Sample Frame.

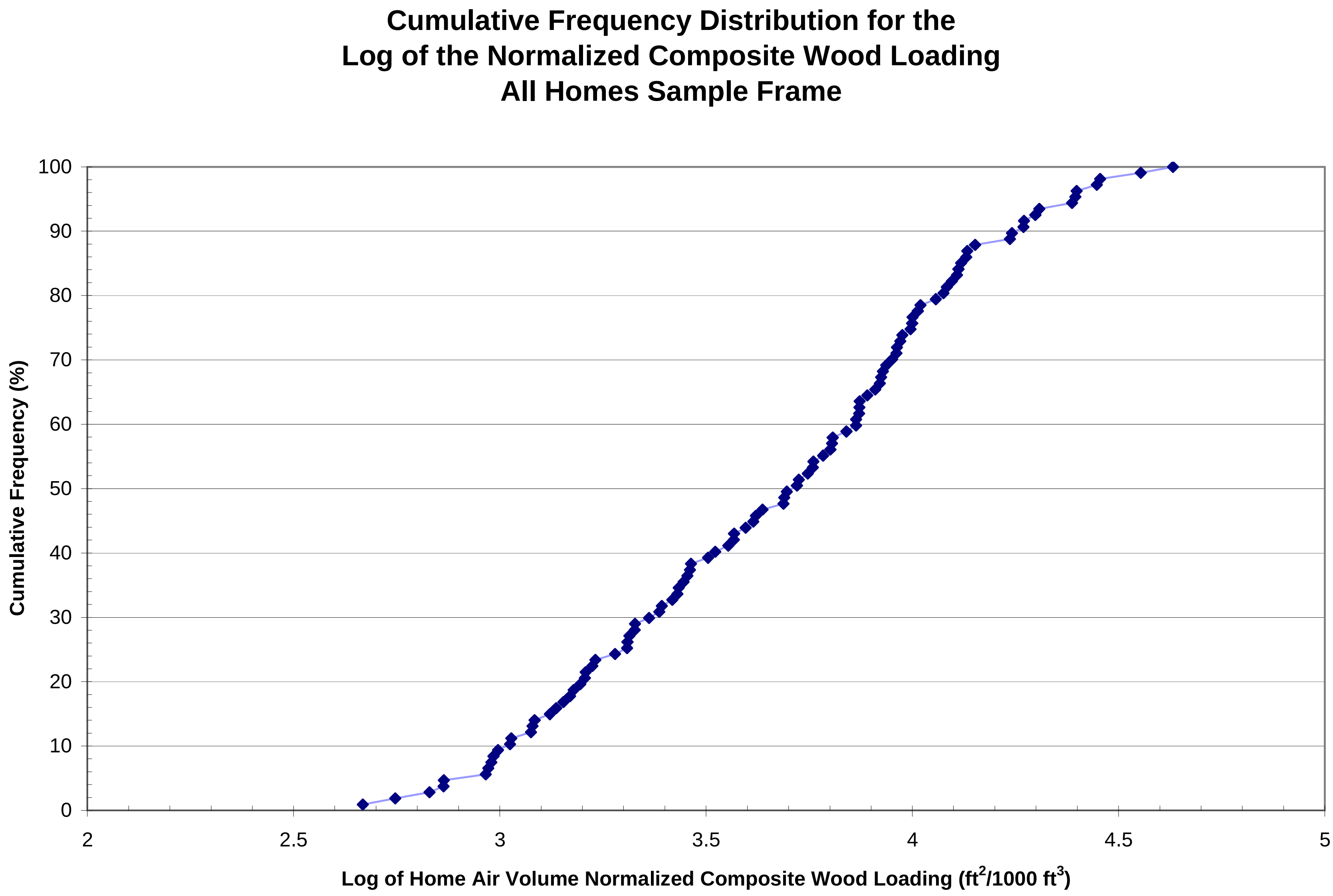


Figure 37. Cumulative frequency distribution for the log of the normalized composite wood loading – All Homes Sample Frame.

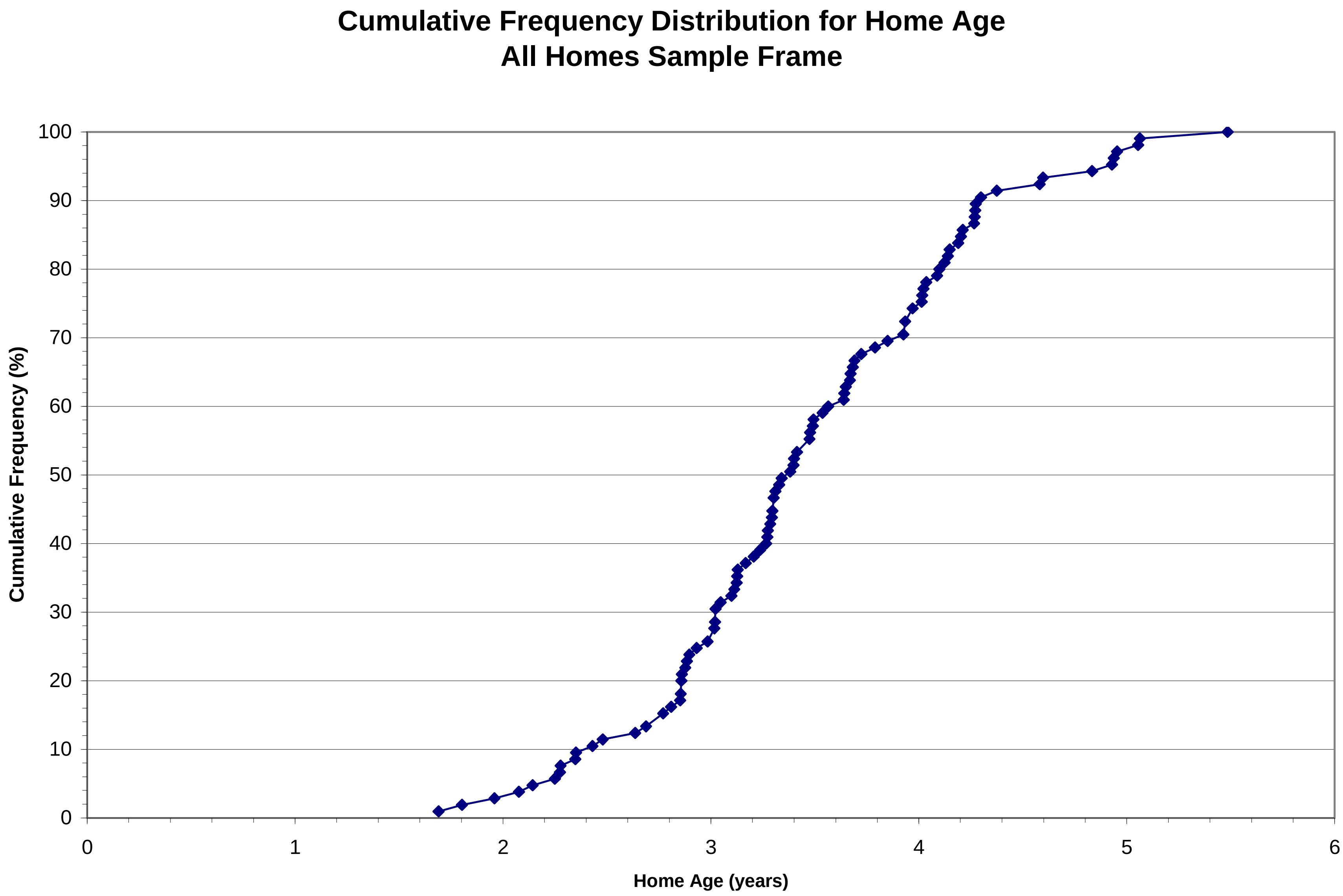
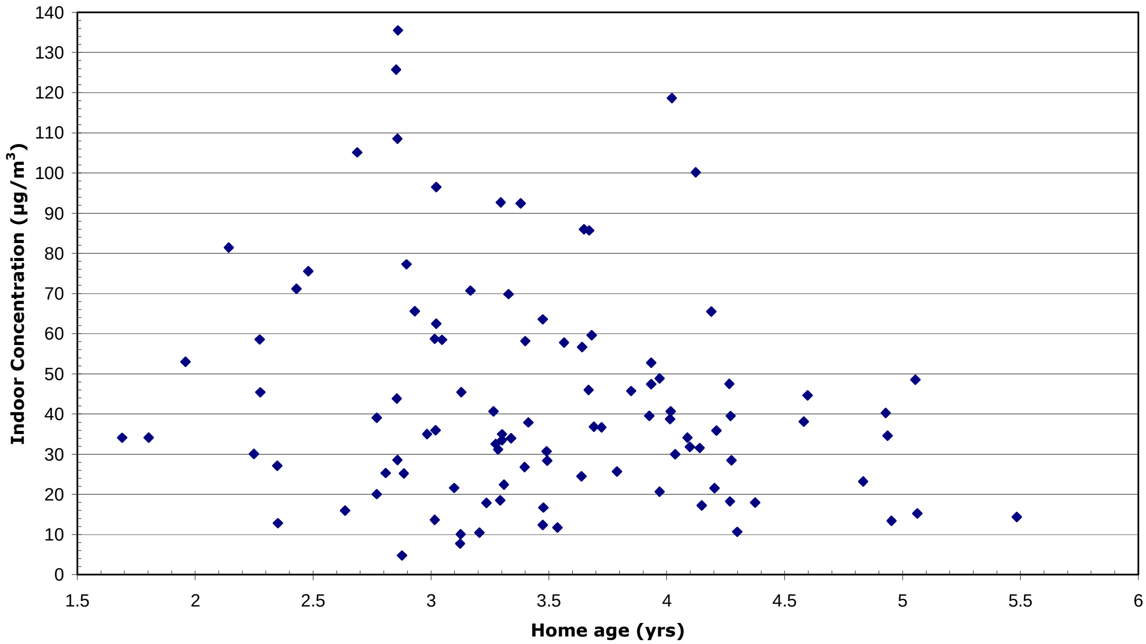


Figure 38. Cumulative frequency distribution for home age – All Homes Sample Frame.

Scatter Plot of Home Age and Indoor Formaldehyde Concentrations
All Homes Sample Frame



Scatter Plot of Home Age and Indoor Acetaldehyde Concentration
All Homes Sample Frame

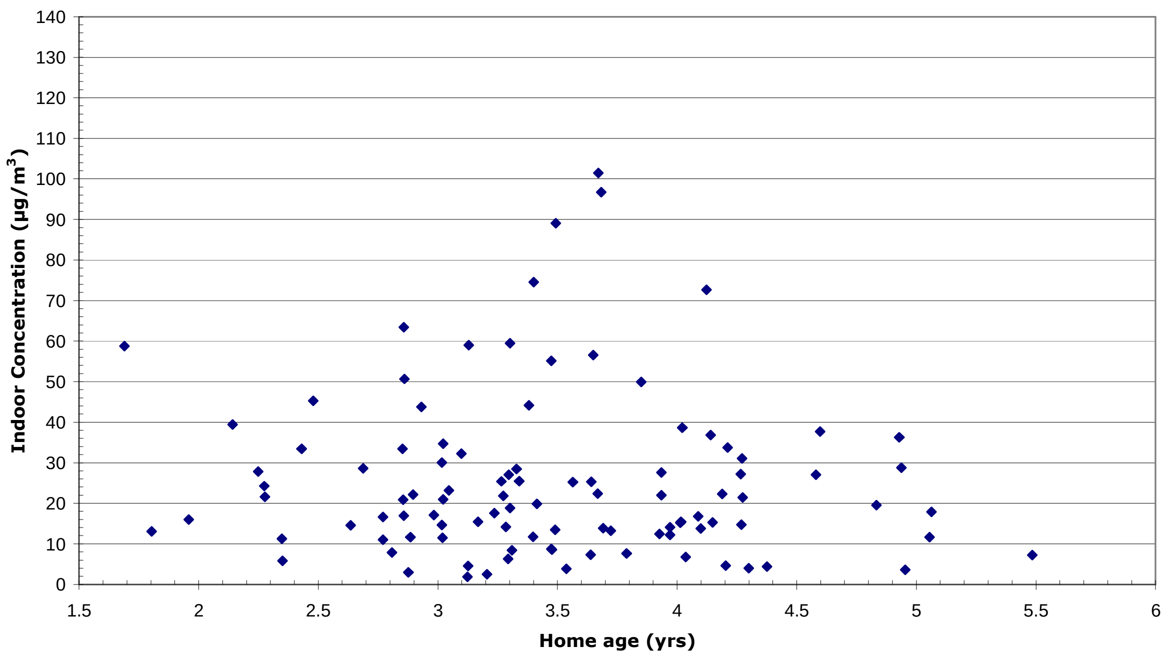
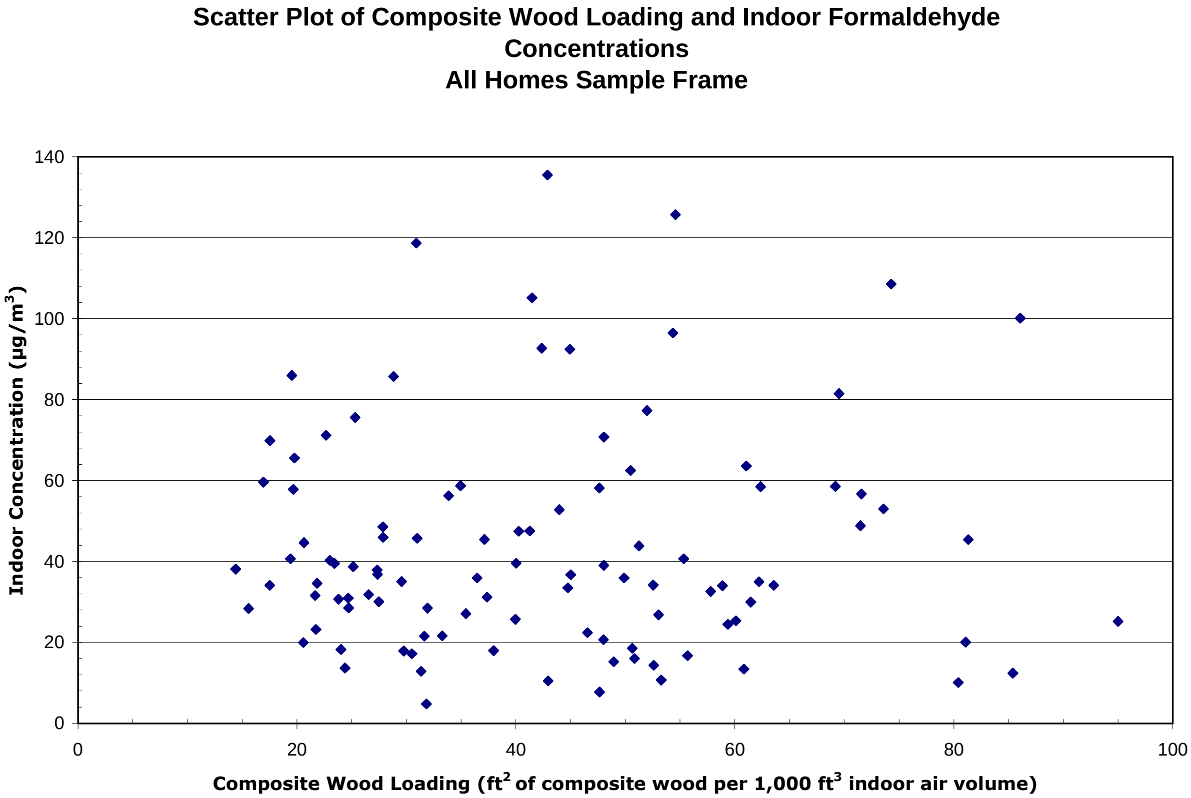


Figure 39. Scatter plots of home age and indoor formaldehyde and acetaldehyde concentrations – All Homes Sample Frame.



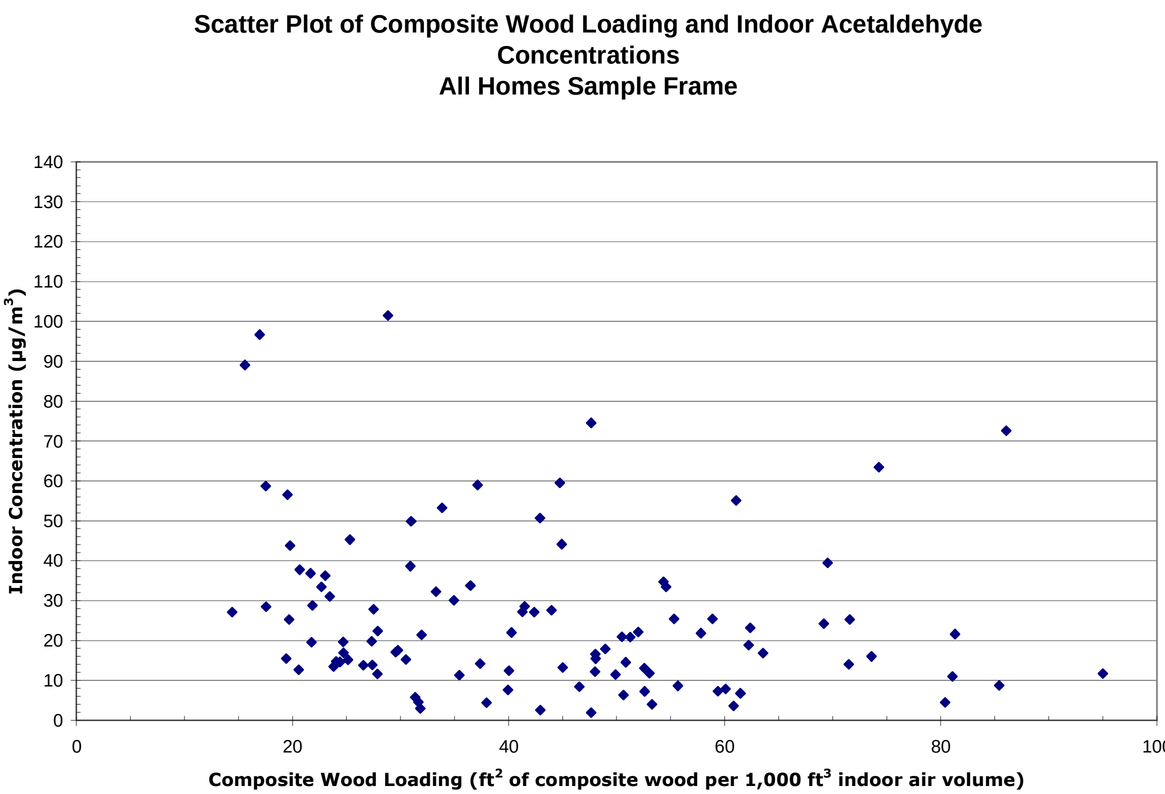
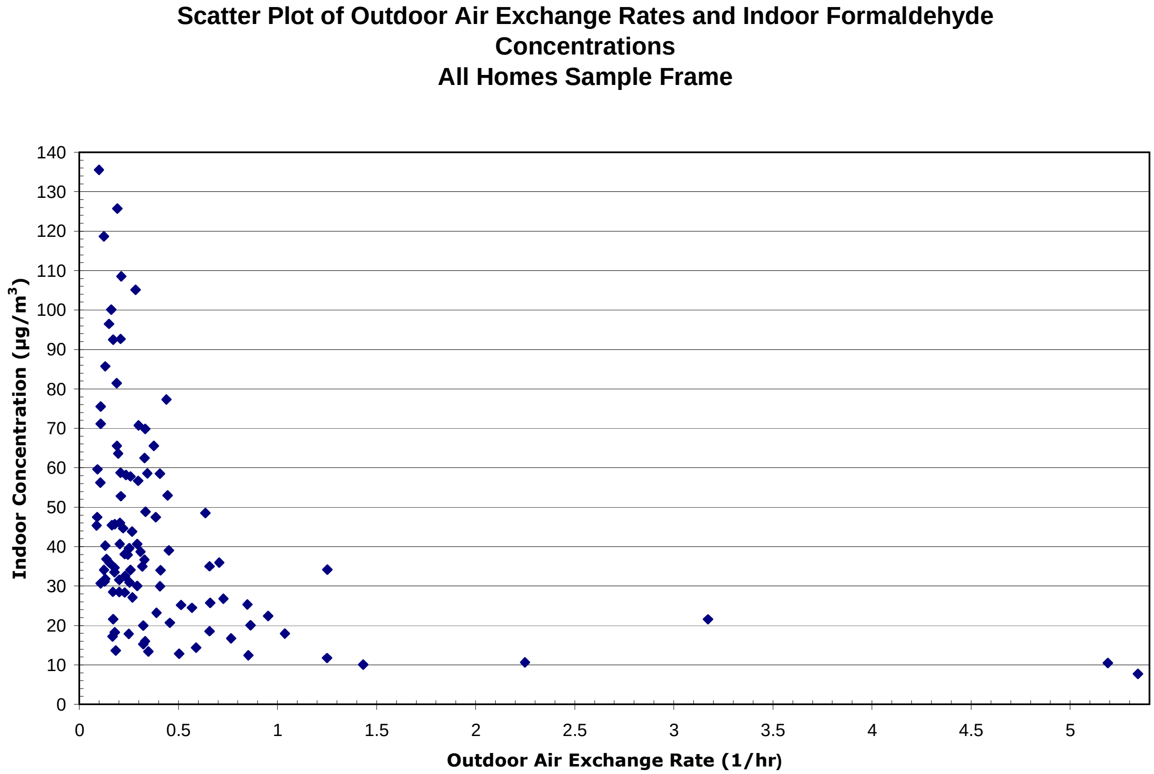


Figure 40. Scatter plots of composite wood loading and indoor formaldehyde and acetaldehyde concentrations – All Homes Sample Frame.



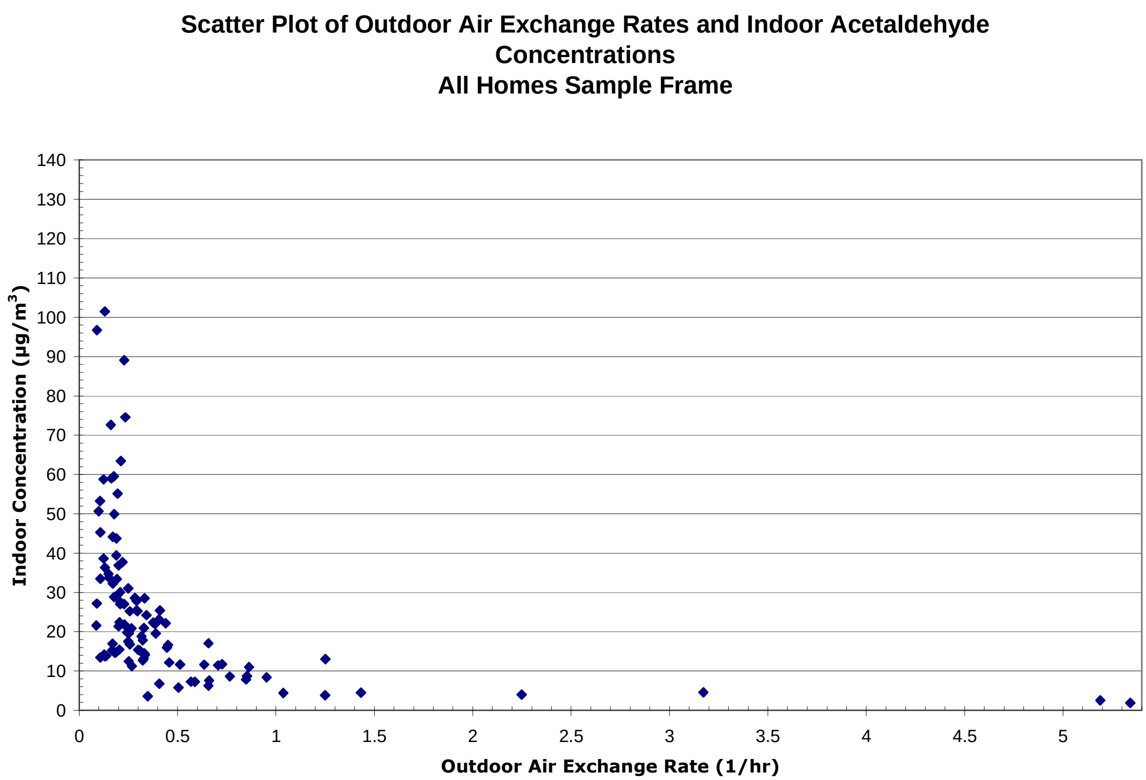
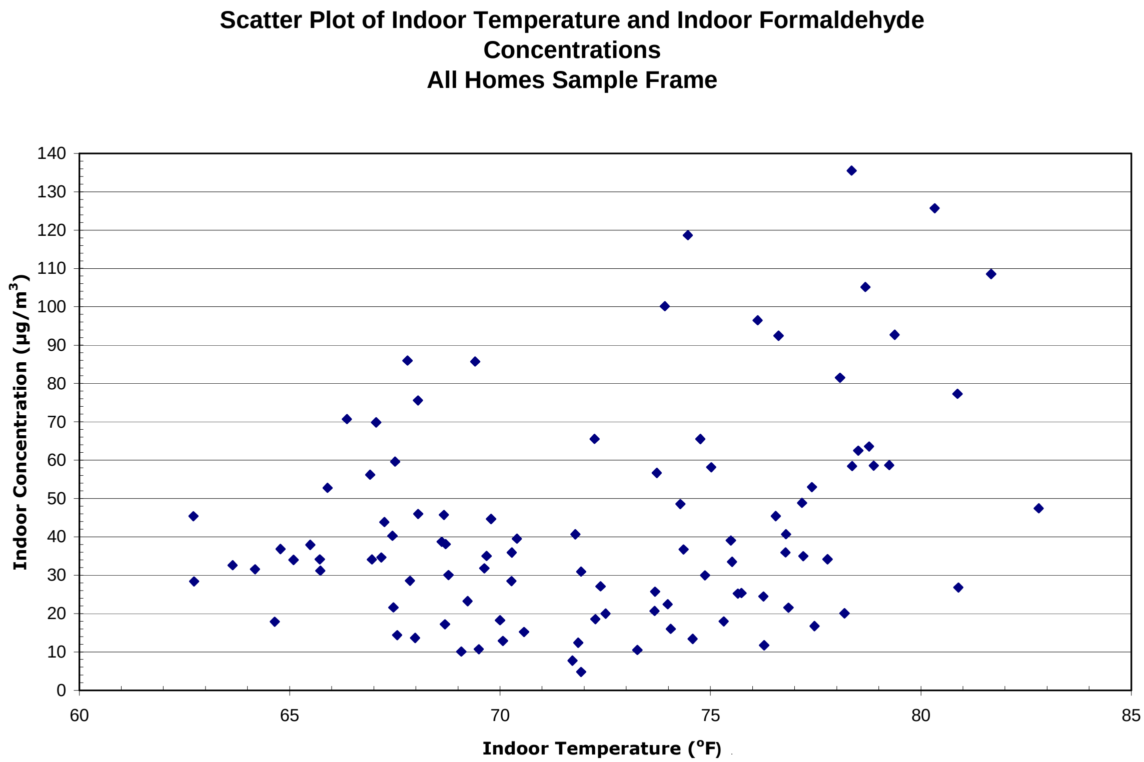


Figure 41. Scatter plots of outdoor air exchange rates and indoor formaldehyde and acetaldehyde concentrations – All Homes Sample Frame.



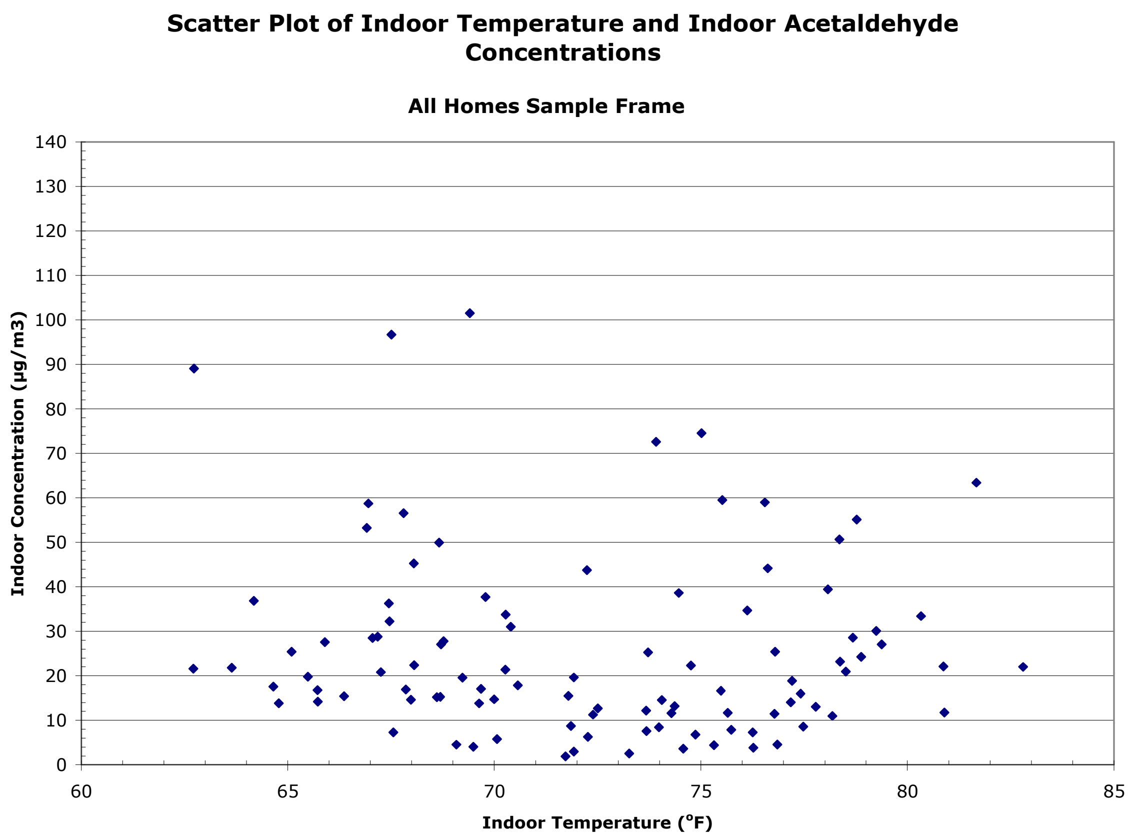
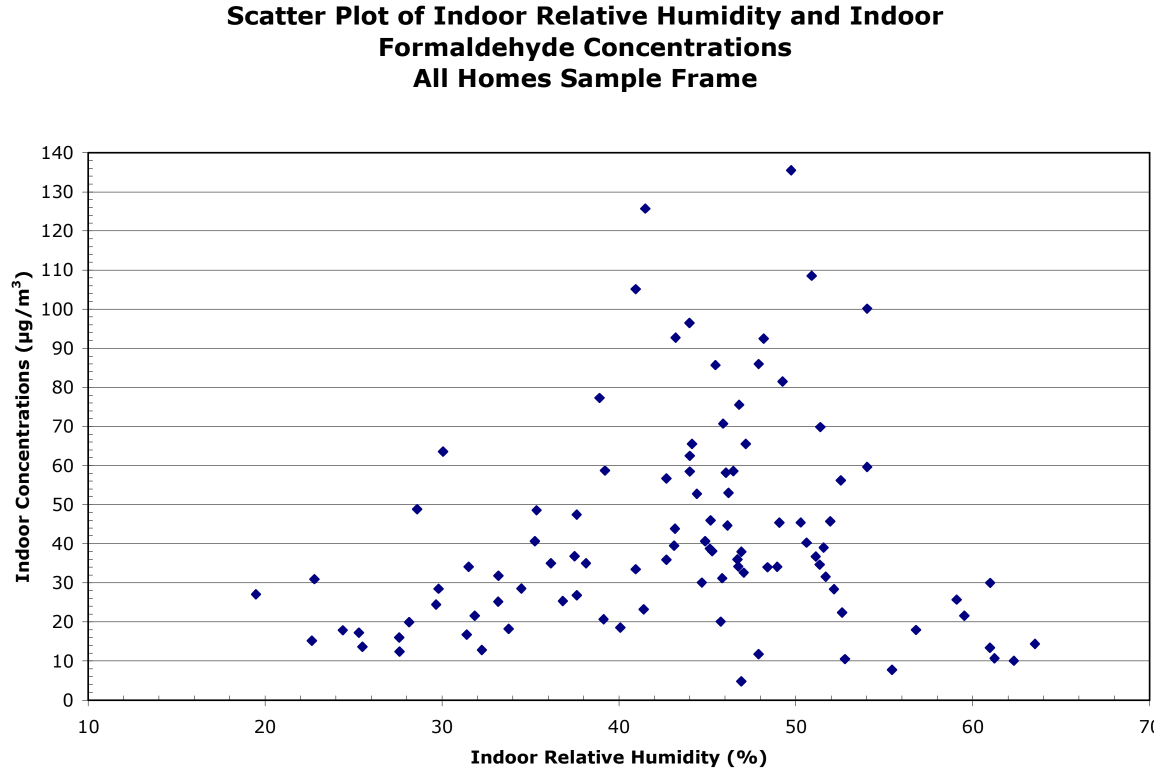


Figure 42. Scatter plots of indoor temperature and indoor formaldehyde and acetaldehyde concentrations – All Homes Sample Frame.



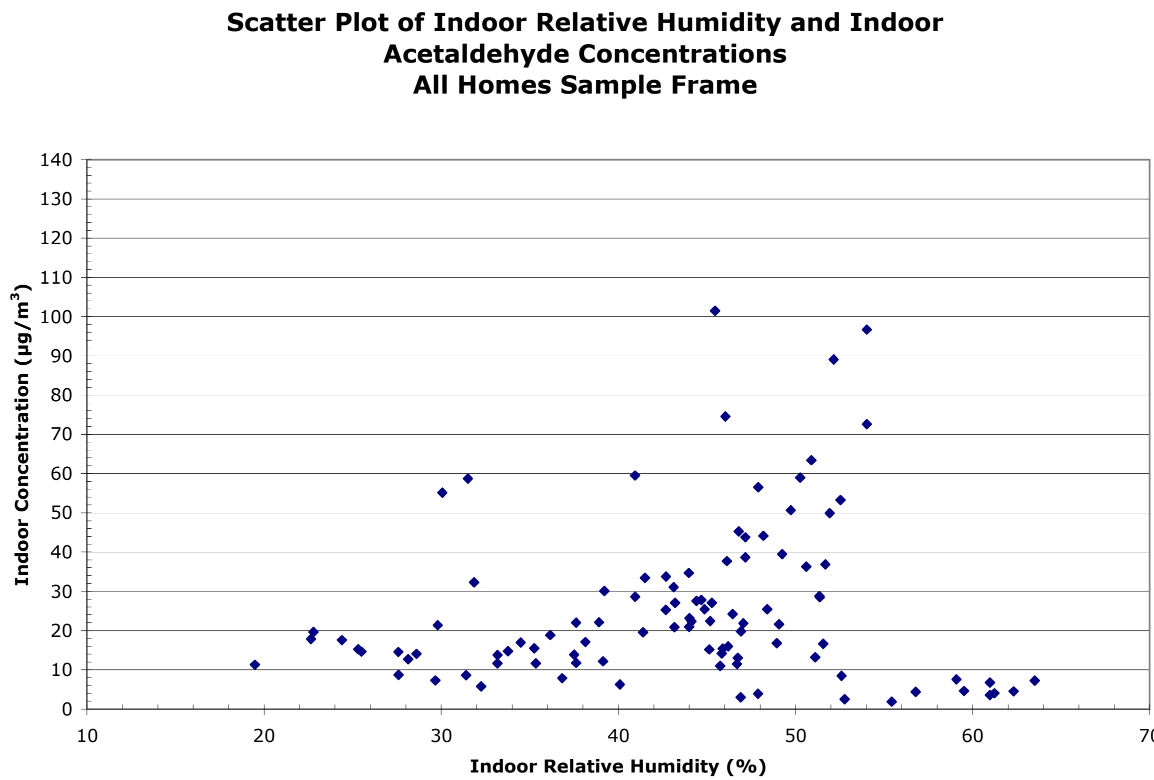
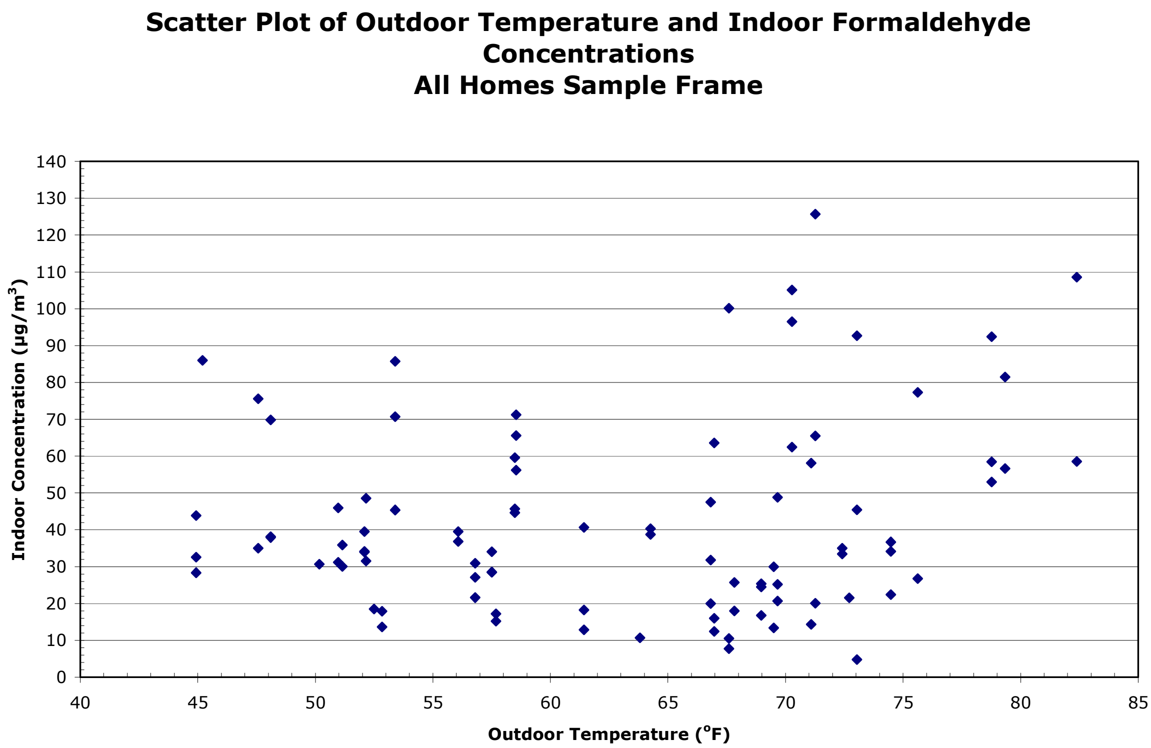


Figure 43. Scatter plots of indoor relative humidity and indoor formaldehyde and acetaldehyde concentrations – All Homes Sample Frame.



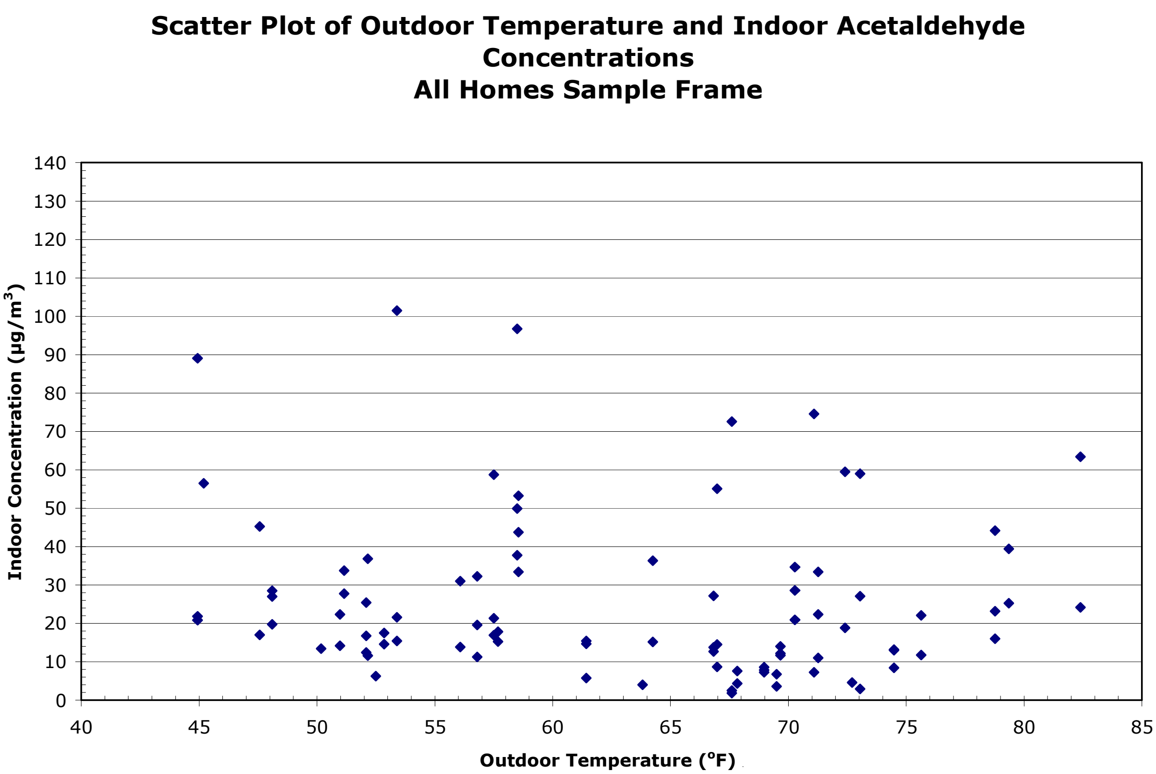
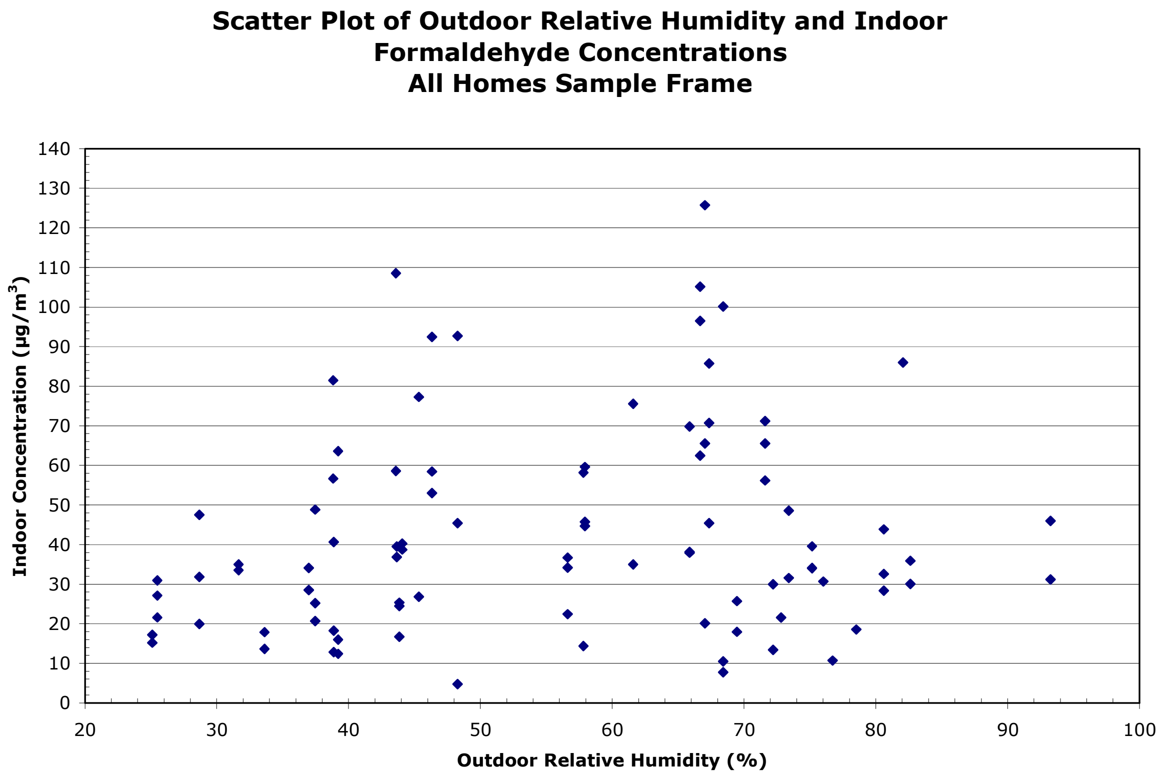


Figure 44. Scatter plots of outdoor temperature and indoor formaldehyde and acetaldehyde concentrations – All Home Sample Frame.



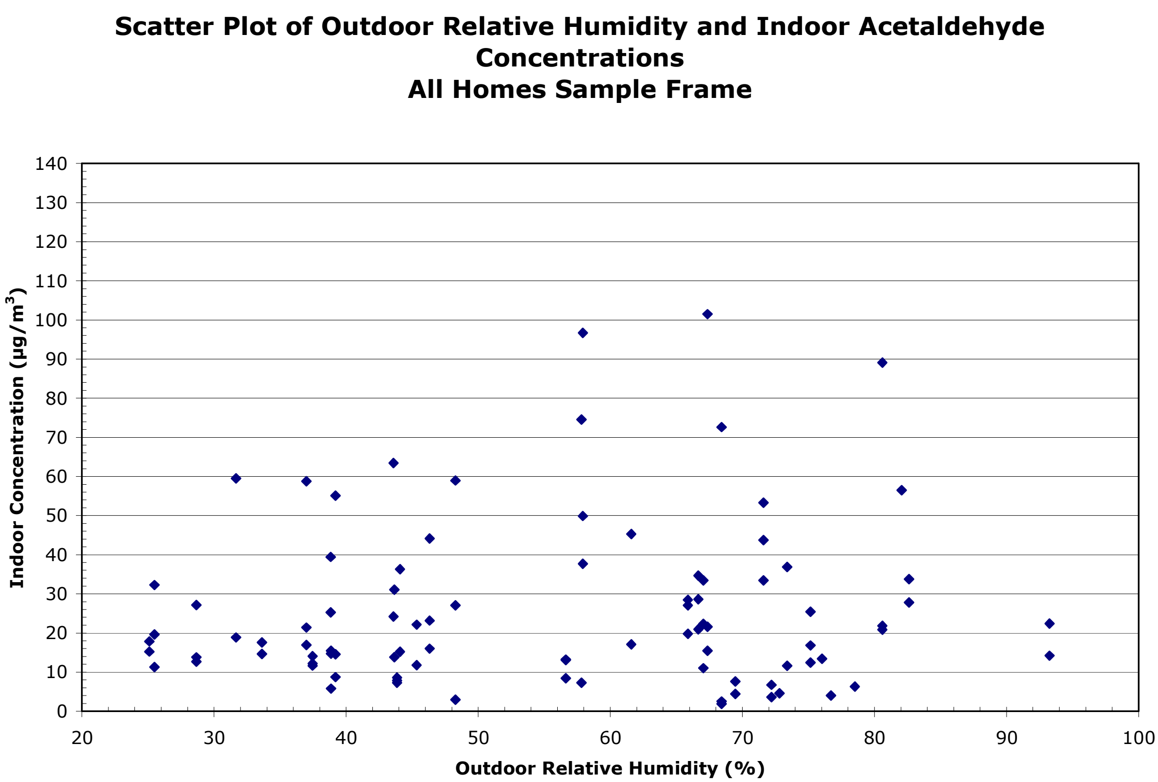


Figure 45. Scatter plots of outdoor relative humidity and indoor formaldehyde and acetaldehyde concentrations – All Homes Sample Frame.

Table 2. Percentages of air contaminant and PFT field samples, blanks, and duplicates successfully collected and analyzed.

Percentages of Air Contaminant and PFT Field Samples, Blanks, and Duplicates Successfully Collected and Analyzed				
	Field Samples Deployed	Field Samples [a] Successfully Collected and Analyzed (%)	Field Sample Blanks [b] Successfully Collected and Analyzed (%)	Field Sample Duplicates [c] Successfully Collected and Analyzed (%)
Volatile Organic Compounds	208	99	10	10
Formaldehyde/Acetaldehyde	221	96	10	9
Particulate Matter – $PM_{2.5}$	44	98	12	10
Nitrogen Dioxide	45	100	12	10
Carbon Monoxide	206	98	NA	9
PFT CATS Samplers	167	99	11	12
QA/QC Goal		98	10	10

a) Percentage of total number of samples excluding field sample blanks that were successfully collected and analyzed.
b) Percentage of field sample blanks successfully collected and analyzed – based upon total successfully collected and analyzed samples less duplicate and blank samples.
c) Percentage of field sample duplicates successfully collected and analyzed – based upon total successfully collected and analyzed samples less duplicate and blank samples.

Table 3. Summer-North field session field blank analyses for volatile organic compounds, including formaldehyde and acetaldehyde.

Summer-North Field Session Field Blank Analyses (ng)					
Compound	Method Mass Detection Limit	Sample ID 006-vb-080806	Sample ID 021-vb-081606	Sample ID 033-vb-082406	Average Blank Sample Mass
		Mass [a]	Mass [a]	Mass [a]	Mass [a]
Acetaldehyde	9	MDL	MDL	49	19
Benzene	3.5	MDL	MDL	MDL	1.8
2-Butoxyethanol	1.9	MDL	MDL	MDL	0.9
Caprolactam	3.4	MDL	MDL	MDL	1.7
1,4-Dichlorobenzene	2.9	MDL	MDL	MDL	1.5
Ethylene glycol	16	MDL	MDL	MDL	8.2
Formaldehyde	9	MDL	MDL	17	8.7
Hexanal	1.4	MDL	MDL	MDL	0.7
n-Hexane	4.2	MDL	MDL	MDL	2.1
d-Limonene	4.2	MDL	MDL	MDL	2.1
1-Methyl-2-pyrrolidinone	6.0	MDL	MDL	MDL	3.0
Naphthalene	2.0	MDL	MDL	MDL	1.0
Phenol	2.8	3.7	MDL	MDL	2.2
alpha-Pinene	3.0	MDL	MDL	MDL	1.5
Styrene	3.1	MDL	MDL	MDL	1.6
Tetrachloroethene	4.7	MDL	MDL	MDL	2.3
Toluene	4.9	MDL	MDL	MDL	2.5
Trichloromethane	4.9	MDL	MDL	MDL	2.4
1,2,4-Trimethylbenzene	3.3	MDL	MDL	MDL	1.6
Vinyl acetate	5.6	MDL	MDL	MDL	2.8
m, p-Xylene	3.8	MDL	MDL	MDL	1.9
o-Xylene	3.2	MDL	MDL	MDL	1.6

a) Blanks with a mass below the method mass detection limit are designated as “MDL” and were assigned a value of one half the method mass detection limit for calculating the average field blank sample mass.

Table 4. Summer-South field session field blank analyses for volatile organic compounds including formaldehyde and acetaldehyde.

Summer-South Field Session Field Blank Analyses (ng)					
Compound	Method Mass Detection Limit	Sample ID 046-vb-090806	Sample ID 055-vb-091406	Sample ID 067-vb-092006	Average Blank Sample Mass
		Mass [a]	Mass [a]	Mass [a]	Mass [a]
Acetaldehyde	9	MDL	12.7	35	17
Benzene	3.5	MDL	MDL	MDL	1.8
2-Butoxyethanol	1.9	MDL	MDL	MDL	0.9
Caprolactam	3.4	MDL	MDL	MDL	1.7
1,4-Dichlorobenzene	2.9	MDL	MDL	MDL	1.5
Ethylene glycol	16	MDL	MDL	MDL	8.2
Formaldehyde	9	MDL	15.9	MDL	8.3
Hexanal	1.4	MDL	MDL	MDL	0.7
n-Hexane	4.2	MDL	MDL	MDL	2.1
d-Limonene	4.2	MDL	MDL	MDL	2.1
1-Methyl-2-pyrrolidinone	6.0	MDL	MDL	MDL	3.0
Naphthalene	2.0	MDL	MDL	3.2	1.7
Phenol	2.8	MDL	MDL	24	8.8
alpha-Pinene	3.0	MDL	MDL	MDL	1.5
Styrene	3.1	MDL	MDL	11	4.6
Tetrachloroethene	4.7	MDL	MDL	MDL	2.3
Toluene	4.9	MDL	MDL	MDL	2.5
Trichloromethane	4.9	MDL	MDL	MDL	2.4
1,2,4-Trimethylbenzene	3.3	MDL	MDL	4.2	2.5
Vinyl acetate	5.6	MDL	MDL	MDL	2.8
m, p-Xylene	3.8	MDL	MDL	MDL	1.9
o-Xylene	3.2	MDL	MDL	MDL	1.6

a) Blanks with a mass below the method mass detection limit are designated as “MDL” and were assigned a value of one half the method mass detection limit for calculating the average field blank sample mass.

Table 5. Winter-North field session field blank analyses for volatile organic compounds including formaldehyde and acetaldehyde.

Winter-North Field Session Field Blank Method Mass Detection Limit (ng)										
Compound	Method Mass Detection Limit	Sample ID 025-vb-022107	Sample ID 101-vb-022207	Sample ID 108-vb-092006	Sample ID 002-vb-030207	Sample ID 114-vb-030607	Sample ID 117-vb-030707	Sample ID 121-vb-030807	Sample ID 119-fb-030707	Average Blank Sample Mass
		Mass [a]	Mass [a]	Mass [a]	Mass [a]	Mass [a]	Mass [a]	Mass [a]	Mass [a]	Mass [a]
Acetaldehyde	9	11	15	MDL	22	9.4	MDL	MDL	25	10
Benzene	3.5	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na [b]	1.8
2-Butoxyethanol	1.9	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	0.9
Caprolactam	3.4	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	1.7
1,4-Dichlorobenzene	2.9	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	1.5
Ethylene glycol	16	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	8.2
Formaldehyde	9	10	MDL	MDL	MDL	MDL	MDL	11	MDL	6.3
Hexanal	1.4	MDL	MDL	MDL	MDL	3.1	MDL	MDL	na	1.1
n-Hexane	4.2	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	2.1
d-Limonene	4.2	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	2.1
1-Methyl-2-pyrrolidinone	6.0	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	3.0
Naphthalene	2.0	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	1.0
Phenol	2.8	3.9	5.2	MDL	MDL	MDL	MDL	MDL	na	2.3
alpha-Pinene	3.0	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	1.5
Styrene	3.1	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	1.6
Tetrachloroethene	4.7	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	2.3
Toluene	4.9	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	2.5
Trichloromethane	4.9	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	2.4
1,2,4-Trimethylbenzene	3.3	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	1.6
Vinyl acetate	5.6	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	2.8
m,p-Xylene	3.8	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	1.9
o-Xylene	3.2	MDL	MDL	MDL	MDL	MDL	MDL	MDL	na	1.6

a) Blanks with a mass below the method mass detection limit are designated as “MDL” and were assigned a value of one half the method mass detection limit for calculating the average field blank sample mass.
b) na: Sample 119-fb-030707 is an additional formaldehyde and acetaldehyde blank, no additional volatile organic compound blank.

Table 6. Winter-South field session field blank analyses for volatile organic compounds including formaldehyde and acetaldehyde.

Winter-South Field Session Field Blank Analyses (ng)							
Compound	Method Mass Detection Limit	Sample ID 039-vb-012407	Sample ID 058-vb-013107	Sample ID 080-vb-013007	Sample ID 088-vb-020507	Sample ID 091-vb-030607	Average Blank Sample Mass (ng)
		Mass [a]	Mass [a]	Mass [a]	Mass [a]	Mass [a]	Mass [a]
Acetaldehyde	9	MDL	9.4	MDL	11	MDL	6.8
Benzene	3.5	MDL	MDL	MDL	MDL	MDL	1.8
2-Butoxyethanol	1.9	MDL	MDL	MDL	MDL	MDL	0.9
Caprolactam	3.4	MDL	MDL	MDL	MDL	MDL	1.7
1,4-Dichlorobenzene	2.9	MDL	MDL	MDL	MDL	MDL	1.5
Ethylene glycol	16	MDL	MDL	MDL	MDL	MDL	8.2
Formaldehyde	9	MDL	MDL	MDL	22	MDL	8.0
Hexanal	1.4	MDL	MDL	6.8	MDL	MDL	1.9
n-Hexane	4.2	MDL	MDL	MDL	MDL	MDL	2.1
d-Limonene	4.2	MDL	MDL	9.2	MDL	MDL	3.5
1-Methyl-2-pyrrolidinone	6.0	MDL	MDL	MDL	MDL	MDL	3.0
Naphthalene	2.0	MDL	MDL	MDL	MDL	MDL	1.0
Phenol	2.8	MDL	MDL	4.5	3.3	MDL	2.4
alpha-Pinene	3.0	MDL	MDL	MDL	MDL	MDL	1.5
Styrene	3.1	4.2	MDL	4.0	MDL	MDL	2.6
Tetrachloroethene	4.7	MDL	MDL	MDL	MDL	MDL	2.3
Toluene	4.9	MDL	MDL	MDL	MDL	MDL	2.5
Trichloromethane	4.9	MDL	MDL	MDL	MDL	MDL	2.4
1,2,4-Trimethylbenzene	3.3	MDL	MDL	MDL	MDL	MDL	1.6
Vinyl acetate	5.6	MDL	MDL	MDL	MDL	MDL	2.8
m,p-Xylene	3.8	MDL	MDL	MDL	MDL	MDL	1.9
o-Xylene	3.2	MDL	MDL	MDL	MDL	MDL	1.6

a) Blanks with a mass below the method mass detection limit are designated as "MDL" and were assigned a value of one half the method mass detection limit for calculating the average field blank sample mass.

Table 7. Precision of volatile organic compound measurements over a 24-hour period.

Precision of Volatile Organic Compounds Concentrations (µg/m^3)											
	Absolute Precision [a]						Relative Precision [b]				
Compound	N	Min	Max	Mean	Standard Deviation	Relative Standard Deviation	Min	Max	Mean	Standard Deviation	Relative Standard Deviation
Acetaldehyde	17	0.1	7.2	1.7	2.2	1.3	0.01	0.33	0.12	0.12	0.98
Benzene	13	0.01	0.9	0.2	0.3	1.4	0.01	0.11	0.05	0.04	0.75
2-Butoxyethanol	12	1E-4	8.4	1.3	2.3	1.7	3E-4	1.03	0.19	0.27	1.46
Caprolactam	0	na	na	na	na	na	na	na	na	na	na
1,4-Dichlorobenzene	1	0.003	0.003	0.003	-	-	0.01	0.01	0.01	-	-
Ethylene glycol	6	0.4	8.1	3	2.9	0.9	0.07	0.35	0.15	0.11	0.72
Formaldehyde	17	0.05	18	4.0	5.0	1.2	0.01	0.37	0.11	0.12	0.93
Hexanal	13	0.002	2.9	0.7	0.7	1.0	3E-4	0.17	0.06	0.06	0.88
n-Hexane	13	0.01	1.1	0.3	0.3	1.0	0.01	0.40	0.10	0.10	1.01
d-Limonene	13	0.03	3.7	1.1	1.1	1.0	0.003	0.27	0.07	0.08	1.14
1-Methyl-2-pyrrolidinone	4	0.01	0.1	0.1	0.03	0.6	0.01	0.08	0.06	0.03	0.53
Naphthalene	15	0.002	0.1	0.02	0.03	1.2	0.003	0.17	0.06	0.05	0.86
Phenol	18	0.02	0.7	0.2	0.1	0.7	0.01	0.60	0.16	0.15	0.94
alpha-Pinene	13	0.004	2.4	1.0	1.0	1.0	0.001	0.09	0.04	0.03	0.73
Styrene	15	0.001	1.2	0.3	0.3	1.1	2E-4	0.67	0.27	0.24	0.90
Tetrachloroethene	4	5E-4	0.1	0.04	0.04	0.8	5E-4	0.12	0.06	0.05	0.84
Toluene	18	0.02	3	0.7	0.8	1.2	0.01	0.24	0.06	0.06	0.99
Trichloromethane	6	0.02	0.3	0.1	0.1	1.0	0.02	0.15	0.08	0.05	0.67
1,2,4-Trimethylbenzene	16	0.00	0.8	0.2	0.2	1.3	0.00	0.37	0.08	0.10	1.25
Vinyl acetate	0	na	na	na	na	na	na	na	na	na	na
m,p-Xylene	17	0.01	2.9	0.5	0.8	1.5	5E-4	0.37	0.07	0.09	1.22
o-Xylene	15	0.01	0.8	0.2	0.3	1.4	0.002	0.36	0.07	0.09	1.27

a) Absolute precision is the absolute difference between the results of the sample pair.
b) Relative precision is the relative standard deviation of the results of the sample pair.

Table 8. Winter-North field session field blank analyses for nitrogen dioxide and $PM_{2.5}$ particulate matter.

Winter-North Field Session Field Blank Analyses (µg)						
Week	Sample ID (Nitrogen Dioxide)	Method Mass Detection Limit	NO_2 [a] mass	Sample ID ($PM_{2.5}$ Particulate Matter)	Method Mass Detection Limit	$PM_{2.5}$ [a] mass
1	025-NB-022107	0.8	MDL	025-PB-022107	1	-3
1	101-NB-022207	0.8	MDL	101-PB-022207	1	-1
	Week 1 Average Blank Sample Mass		0.0	Week 1 Average Blank Sample Mass		-2
2	002-NB-030107	0.8	MDL	002-PB-030107	1	-1
2	108-NB-022807	0.8	MDL	108-PB-022807	1	-3
	Week 2 Average Blank Sample Mass		0.0	Week 2 Average Blank Sample Mass		-2
3	114-NB-030607	0.8	MDL	114-PB-030607	1	-3
	Week 3 Average Blank Sample Mass		0.0	Week 3 Average Blank Sample Mass		-3

a) Nitrogen dioxide blanks with a mass below the method mass detection limit are designated as “MDL” and were assigned a value of zero for calculating the average field blank sample mass. The average mass for the $PM_{2.5}$ field blanks was calculated directly from the measured masses of the field blanks.

Table 9. Precision for carbon dioxide, carbon monoxide, nitrogen dioxide, and $PM_{2.5}$ measurements over a 24-hour period.

Precision Of Carbon Dioxide, Carbon Monoxide, Nitrogen Dioxide, and $PM_{2.5}$ Measurements											
	Absolute Precision [a]						Relative Precision [b]				
Compound	N	Min	Max	Mean	Standard Deviation	Relative Standard Deviation	Min	Max	Mean	Standard Deviation	Relative Standard Deviation
Carbon Dioxide (ppm)	17	1.7	69	16	17	1.1	0.01	0.15	0.02	0.04	1.46
Carbon Monoxide (ppm)	17	0.0	1.5	0.6	0.5	0.8	0.01	1.39	0.53	0.50	0.93
Nitrogen Dioxide (µg/m^3)	4	0.2	0.3	0.2	0.1	0.4	0.01	0.03	0.02	0.01	0.25
Particulate Matter $PM_{2.5}$ (µg/m^3)	4	0.6	3.4	2.0	1.2	0.6	0.04	0.28	0.11	0.11	0.99

a) Absolute precision is the absolute difference between the results of the sample pair.
b) Relative precision is the relative standard deviation of the results of the sample pair.

Table 10. Summer and field session field blank analyses for PFT measurements.

Summer and Winter Field Session Field Blank Analyses (pL)			
Group	Method Volume Detection Limit	Sample ID	Blank Volume (pL) [d]
Summer –1 [a]	0.001	006-tb-080806	0.021
		Summer-1 Blank Average Volume	0.021
Summer –2 [b]	0.001	067-TB-092006	MDL
Summer -2	0.001	055-TB-091406	MDL
Summer -2	0.001	046-TB-090806	0.022
Summer -2	0.001	033-TB-082406	MDL
Summer -2	0.001	021-TB-081606	0.043
		Summer-2 Blank Volume Average	0.013
Winter [c]	0.001	002-tb-030107	0.014
Winter	0.001	025-tb-022107	0.024
Winter	0.001	039-tb-012407	0.022
Winter	0.001	058-tb-013107	0.010
Winter	0.001	080-tb-013007	0.010
Winter	0.001	088-tb-020507	0.029
Winter	0.001	091-tb-020607	0.019
Winter	0.001	101-tb-022207	0.009
Winter	0.001	108-tb-022807	0.009
Winter	0.001	114-tb-030607	0.028
		Winter Blank Volume Average	0.017

a) Summer-1: This blank sample was used with the first 12 home of the Summer-North field session.

b) Summer-2: These blank samples were used with homes 13–72 of the Summer-North and Summer-South field sessions.

c) Winter: These blank samples were used with all of Winter homes, Winter-North and Winter-South field sessions.

d) Blanks with a volume below the method volume detection limit are designated as “MDL” and were assigned a value of one half the method volume detection limit for calculating the average field blank sample volume.

Table 11. Precision of PFT outdoor air exchange rates measured over the 24-hour Test Day and the following two-week period.

Precision of PFT Outdoor Exchange Rate Measurement											
	Absolute Precision (ach)[a]						Relative Precision (ach)[b]				
	N	Min	Max	Mean	Standard Deviation	Relative Standard Deviation	Min	Max	Mean	Standard Deviation	Relative Standard Deviation
24-Hour Measurement	11	0.002	0.03	0.01	0.01	0.76	0.003	0.05	0.02	0.01	0.60
2-Week Measurement	4	0.002	0.02	0.01	0.01	0.87	0.01	0.01	0.01	0.005	0.42

a) Absolute precision is the absolute difference between the results of the sample pair.
b) Relative precision is the relative standard deviation of the results of the sample pair.

Table 12. Comparison of PFT measurements in the first and second zones of the home.

PFT Measurements in Two Zones										
					PFT Sample #1		PFT Sample #2		Difference	
Home ID	Season	FAU Hours On	Window ft^2/hrs	Sample Period	Location	ACH	Location	ACH	Absolute [b] (ach)	Relative [c]
019	Winter	5.5	0	24 hr	1st Floor Family Room	0.11	2nd Floor Loft	0.10	0.01	0.07
099	Winter	na [a]	na [a]	2 week	1st Floor Family Room	0.15	2nd Floor Master Bed	0.14	0.01	0.05
116	Winter	0	50.5	24 hr	1st Floor Family Room	0.22	2nd Floor Bonus Room	0.16	0.06	0.22

a) na: No data were collected over the two-week period.
b) Absolute precision is the absolute difference between the results of the sample pair.
c) Relative precision is the relative standard deviation of the results of the sample pair.

Table 13. Home recruitment results for each region-season.

Home Recruitment Results

	Summer North	Summer South	Fall North	Winter South	Winter North	Total
Homes that received mailer	1,358	1,408	15	1,486	1,500	5,764
Homes from UCB Mail Survey	25%	23%	53%	21%	12%	20%
Called to express interest in study	95	41	10	62	71	279
Interest rate	7%	3%	67%	4%	5%	5%
Homes contacted by phone	471	201	10	264	73	1,019
Disconnected phone number	20	4	0	18	0	42
Not qualified for study	18	3	0	3	2	26
Refused/hung up/not interested	81	18	0	31	4	134
Wrong address	3	8	0	7	22	40
Language barrier	4	2	0	2	0	8
Homes recruited	32	31	4	33	32	132
Homes recruited with mechanical outdoor [a] air ventilation systems	18	4	0	4	17	43
Homes recruited from UCB Mail Survey	53%	55%	50%	36%	31%	44%
Recruitment rate for mailers	2%	2%	27%	2%	2%	2%
Recruitment rate for calls	7%	15%	40%	13%	44%	13%

a) Includes homes with nighttime ventilation cooling systems.

Note: Not all homes that received a mailer also received a phone call. The number of homes recruited in the winter includes 10 homes recruited for a seasonal repeat test in both the North and South regions and the four homes recruited for the fall were all repeats from the summer session. Total homes recruited was 108 with 24 seasonal repeat recruits.

Table 14. Home sample comparison for the field study to the UCB mail survey sample by geographical strata.

Comparison of Field Study Sample to UCB Mail Survey Sample [a]				
	UCB Mail Survey Total Homes	UCB Mail Survey % of Total	Field Study Total Homes	Field Study % of Total
Sacramento/Delta Region	177	21	42	39
Southern California Coastal	175	21	17	16
Rest-of-State	489	58	49	45
Total	841	100	108	100

a) Total homes and percentage of total homes for the UCB mail survey sample three geographical strata and those recruited for this field study.

Table 15. Home characteristics-1.

Home Characteristic Variables												
Variable	N [a]	Mean	Standard Dev.	Geometric Mean	Geometric Std. Dev.	Min	10%	25%	50%	75%	90%	Max
Age of House (years)	105	3.5	0.8	2.2	12	1.7	2.4	3.0	3.4	4.0	4.3	5.5
Area (ft^2)	108	2,669	742	2,566	1.3	1,283	1,718	2,166	2,703	3,152	3,647	5,064
Volume (ft^3)	108	24,343	7,484	23,240	1.4	10,667	16,010	19,063	23,355	28,374	34,194	55,613
Openable Window Area/Floor Area	108	0.06	0.01	0.06	1.2	0.03	0.05	0.06	0.06	0.07	0.08	0.1
Garage Outdoor Air Venting (ft^2)	93	0.6	0.7	-	-	0.0	0.0	0.0	0.7	1.0	1.0	4.0
Possible Fungal Growth (ft^2)	107	0.01	0.1	-	-	0.0	0.0	0.0	0.0	0.0	0.0	1.0
Moisture Staining (ft^2)	107	0.2	0.9	-	-	0.0	0.0	0.0	0.0	0.0	0.0	9.0
Interior Finish Materials (ft^2)												
Floor - vinyl & linoleum	107	141	194	-	-	0.0	0.0	0.0	42	240	462	715
Floor - stone & ceramic tile	107	393	342	-	-	0.0	0.0	82	349	650	857	1,421
Floor - real wood	107	174	308	-	-	0.0	0.0	0.0	0.0	270	718	1,156
Floor - concrete & brick	107	6.5	65	-	-	0.0	0.0	0.0	0.0	0.0	0.0	675
Floor – rug	107	40	66	-	-	0.0	0.0	0.0	0.0	56	152	254
Floor - carpet	107	1,326	511	996	7.9	210	695	975	1,311	1,683	2,021	2,624
Floor - composite wood	107	39	167	-	-	0.0	0.0	0.0	0.0	0.0	0.0	979
Wall - composite wood	107	0.0	0.0	-	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ceiling - composite wood	107	0.0	0.0	-	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Furniture/cabinetry composite wood	107	990	512	721	7.7	263	422	607	898	1,239	1,749	2,925
Total composite wood	107	1,030	532	746	7.8	263	422	615	925	1,306	1,758	2,925

a) The number of homes with completed data.

Table 16. Home characteristics-2.

Home Characteristic Variables					
Variable	N [a]	%	Variable	N [a]	%
Number of Stories			Range(s)		
- 1 Story	108	34	- Gas fuel	108	2
- 2 Story	108	66	- Electric fuel	108	98
Number of Bedrooms			- Range exhaust ducted outdoor	108	85
- 2 Bedrooms	108	8	Oven(s)		
- 3 Bedrooms	108	20	- Gas fuel	108	27
- 4 Bedrooms	108	46	- Electric fuel	108	73
- 5 Bedrooms	108	19	- Oven exhaust ducted outdoor	108	2
- 6 Bedrooms	108	6	Clothes Dryer		
Number of Bath and Toilette Rooms			- Gas Fuel	103	76
- 2 Rooms	108	26	- Electric Fuel	103	24
- 3 Rooms	108	55	- Exhaust ducted outdoor	103	98
- 4 Rooms	108	14	- Exhaust Leaks	103	11
- 5 Rooms	108	6	FAU System		
Attic Present	107	99	- Gas fuel	81	100
Garage Present	108	100	- Electric fuel	81	0
- Attached	108	99	- T-Stat fan mode – Auto	99	100
- Detached	108	1	- T-Stat fan mode – On	99	0
- Attached door	108	99	Water Heater		
- Weather-stripped attached door	108	100	- Gas fuel	106	98
- Self closing attached door	108	98	- Electric fuel	106	2
- Outdoor air venting	108	97	Portable Air Cleaners Present	101	14
- Used for vehicle parking	108	92	Window Fan Present	108	4
- Living space above	108	60	Window Air Conditioner Present	108	0
- Solvent smell	108	7	- Has Outdoor Air Supply	108	0
- Moisture staining	108	2	Odor Upon Entry	108	27
- Musty smell	108	9	HEPA Filtered Vacuum Cleaner Present	108	39
Foundation Type			Air Fresheners Present	99	20
- Slab	107	97	Fireplaces Present	107	85
- Crawlspace	107	1	- Decorative gas log vented	108	61
- Basement	107	1	- Sealed combustion vented	108	31
			- Unvented gas logs	107	0

a) Number of homes with completed data.

Table 17. Home characteristics-3.

Home Characteristic Variables					
Variable	N [a]	%	Variable	N [a]	%
Primary Kitchen Cabinetry			Overall Home Clutter		
- Composite wood - no interior laminate	108	2	- 1 No clutter	108	49
- Composite wood - interior laminate	108	97	- 2 Some clutter	108	41
- Solid wood	108	1	- 3 Moderately cluttered	108	8
- Metal	108	0	- 4 Very cluttered	108	2
Bathroom Cabinetry			Outdoor Contaminant Sources [b]		
- Composite wood - no interior laminate	108	1	- Busy street or freeway	108	7
- Composite wood - interior laminate	108	99	- Construction or road work	108	3
- Solid wood	108	0	- Dirt or gravel road	108	7
- metal	108	0	- Restaurant	108	8
Overall Cleanliness			- Industrial activity	108	4
- 1 Very clean	108	72	- Open field or crops	108	8
- 2 A bit dirty	108	26	- Gas station	108	13
- 3 Moderately dirty	108	1	- Dry cleaners	108	5
- 4 Very dirty	108	1	- Bus or truck activity	108	0
			- No sources	108	45

a) Number of homes with completed data.
b) Outdoor sources within 500 feet.

Table 18. Homeowner reported home characteristics, renovations, maintenance, and other IAQ related activities-1.

Home Characteristics, Renovations, Maintenance and Other IAQ Related Activities		
Variable	N[a]	%
How many adults live in the home		
- 1	108	8
- 2	108	73
- 3	108	14
- 4	108	4
- 5	108	1
How many children under 18 live in the home		
- 0	108	46
- 1	108	17
- 2	108	25
- 3	108	8
- 4	108	3
- 5	108	1
How many occupants who live in the home are smokers [b]		
- 0	107	97
- 1	107	2
- 2	107	0
- 3	107	1
Do pets live in the home?	106	56
Are shoes worn in the home?	108	57
Are there cloths or drapes that have been dry-cleaned within the last week	104	16

a) Number of homes with completed data.
b) Homes that reported occupants that smoke inside the home were excluded from this study, thus the occupants who live in the home and smoke are ones that report only smoking outside of the home.

Table 19. Homeowner reported home characteristics, renovations, maintenance, and other IAQ related activities-2.

Home Characteristics, Renovations, Maintenance and Other IAQ Related Activities		
Variable	N [a]	%
Have there been any of the following in the home within the past 6 months: (Note: 3 months for repeat)		
Painting	108	32
Caulking	107	12
Carpet installation	108	7
New cabinetry	105	3
New furniture	106	22
Other	82	10
Duct cleaning	107	1
Duct sealing	105	1
Pesticide applications	104	42
Fire/smoke damage	108	0
Mold or moisture remediation	107	6
Are any of the following used in the home:		
Portable air cleaners	103	17
Vacuum cleaners	107	100
Window fans	102	6
Window air conditioners	103	3
Plug-in air fresheners	102	33
Candles	101	58
Incense	101	11
Mothballs	101	7
Hobbies and crafts	95	28
Are any of the following stored in your home or garage:		
Paints, varnishes, paint thinners	107	94
Kerosene, gasoline, propane, lighter fluid, self lighting charcoal	106	70
Pesticides, insecticides, lawn/garden chemicals	108	89
Cleaning supplies, e.g., bleach, detergents	108	100
Latex products	105	61
Are motor vehicles stored in the garage:	108	92

a) Number of homes with completed data.

Table 20. Homeowner reported home characteristics, renovations, maintenance and other IAQ related activities-3.

Home Characteristics, Renovations, Maintenance and Other IAQ Related Activities		
Variable	N [a]	%
How often are the carpets and rugs in the most heavily used rooms vacuumed:		
Twice per week or more often	108	13
About once per week	108	45
About every two weeks	108	26
About every 3 to 4 weeks	108	11
Less often	108	5
What methods, other than sweeping or vacuuming, have been used in the home to clean the carpets?		
Steam cleaning	92	37
Professionally dry cleaned	92	16
Spot cleaned or dry cleaned by homeowner	92	63
Since you have lived in this home, has it had any of the following conditions?		
Significant condensation on windows or other indoor surfaces	108	4
Roof leaks	108	4
Plumbing leaks	108	10
Wall or window leaks	108	13
Flooding	108	3
Poor site drainage	108	6
Bothersome carpet odors	108	2
Bothersome cabinetry odors	108	6
Other unpleasant odors	108	7
Other moisture problems	108	7

a) Number of homes with completed data.

Table 21. Mechanical outdoor air system types and controls.

Mechanical Outdoor Air System Types And Control Variables		
Variable	N [a]	%
Homes with one or more Mechanical Outdoor Air Systems	108	33
Homes with Multiple Mechanical Outdoor Air Systems	108	4
Homes with only a Ducted Outdoor Air Systems (DOA)	108	16
Homes with only a Heat Recovery Ventilator Systems (HRV)	108	6
Homes with Nighttime Cooling Systems (WHF or RAD)	108	11
Homes with Evaporative Cooling Systems	108	1
System Characteristics: System Type	N [b]	%
• FAU with Ducted Outdoor Air (DOA)	40	43
• Heat Recovery Ventilator (HRV)	40	23
• Nighttime Cooling FAU Return Air Damper (RAD)	40	15
• Nighttime Cooling Whole House Fan (WHF)	40	13
• Evaporative Cooler (EC)	40	3
• Window Fan (WF)	40	3
Damper Type		
• Manual	40	30
• Automatic	40	33
• Gravity	40	13
• No damper	40	25
Operation Control Type		
• With the FAU Thermostat	40	45
• On/Off Switch	40	33
• FAU Fan Cycler	40	18
• Timer	40	5
Control Location		
• Home	40	75
• Attic	40	25

a) N represents the number of homes with complete data.
b) N represents the total number of mechanical outdoor air systems.

Table 22. Forced air unit (FAU) heating/cooling system duct leakage measurements.

Forced Air Unit Heating/Cooling System Duct Leakage												
Variable	N	Mean	Standard Dev.	Geometric Mean	Geometric Std. Dev.	Min	10%	25%	50%	75%	90%	Max
FAU Duct [a, b] Leakage (%)	138	11.9	8.7	6.5	21.1	1.9	5.2	7.4	10	13	17	73
FAU Duct Leakage [c] Ratio	119	2.2	1.5	0.1	1051	1.0	1.2	1.5	1.7	2.3	2.9	12.3

		% Homes Fail to Meet CBC Requirement	CBC – 2005 Requirement
FAU Duct Leakage	138	86	< 6%

a) Measured by sealing all supply registers and pressurizing the FAU system to 25 pascals at the return air grille.
b) Measured duct leakage flowrate / total system flow rate, multiplied by 100 (%).
c) Measured duct leakage percentage/6% for homes with duct leakage exceeding 6%.

Table 23. Building envelope air leakage measurements.

Building Envelope Air Leakage												
Variable	N	Mean	Standard Dev.	Geometric Mean	Geometric Std. Dev.	Min	10%	25%	50%	75%	90%	Max
Average Wind [a] Speed (mph)	108	5.8	2.8	5.2	1.7	1.4	2.3	3.9	5.7	7.2	9.5	16
Indoor/Outdoor Temperature Difference (^{0}F)	108	5.4	3.9	-	-	-2.3	0.3	2.2	5.3	8.2	11	14
Effective Leakage [b] Area (in^2)	106	110	36	68	23	56	72	85	104	125	148	261
SLA [c]	107	2.9	0.7	2.0	14	1.4	2.1	2.5	2.9	3.3	3.7	5.6
ACH_{50} [d] (ach)	106	4.9	0.9	4.0	6.9	2.8	3.8	4.3	4.8	5.4	6.2	8.4

a) Collected from local weather station data and averaged over the 24-hour Test Day.
b) Calculated from a multi-point depressurization (0–50 pascals) test using a blower door.
c) SLA calculated by ELA/ft^2 of floor area x 69.44.
d) Measured while the home is depressurized to 50 pascals using a blower door.

Table 24. Home-to-garage air leakage measurements.

Home-to-Garage Air Leakage Measurements												
Variable	N	Mean	Standard Dev.	Geometric Mean	Geometric Std. Dev.	Min	10%	25%	50%	75%	90%	Max
Home-to-Garage Leakage [a] Area EqLA (in^2)	105	22	19	6.3	94	0	6.4	11	16	24	42	97
Garage-to-Outdoor Leakage [a] Area EqLA (in^2)	105	191	135	82	51	38	62	107	156.	243	336	959
Home-to-Garage Pressure [b] (pascals)	107	-48	-2.9	-39	-8.5	-34	-44	-47	-49	-49	-50	-55
Coupling Factor [b, c]	107	0.05	0.05	-	-	0	0	0.01	0.03	0.07	0.12	0.26
Leakage Ratio [d] (%)	105	5.5	3.5	-	-	0	1.9	3.1	4.9	7.1	9.6	18

a) Calculated from two multi-point depressurization tests (0–50 pascals), one with the home-garage door closed and one with the door open. Leakage areas are calculated using a reference pressure of 10 pascals.
b) Measured with the home depressurized to 50 pascals to outdoor air.
c) Calculated from garage-to-outdoor differential pressure / home-to-outdoor differential pressure, 0= no coupling, 1= total coupling.
d) Calculated from home-to-garage leakage area / (home-to-outdoor leakage area + garage-to-outdoor leakage area) x 100. Leakage areas are calculated using a reference pressure of 10 pascals.

Table 25. Window and door opening usage during the 24-hour air testing day and the preceding one-week.

Window and Door Usage for the 24-Hour Test Day and the Preceding One-Week

	N	Mean	Standard Dev.	Geometric Mean	Geometric Standard Dev.	Min	10%	25%	50%	75%	90%	Max
Windows/Doors												
Test Day 24 hr Usage [a] (ft^2-hrs)	108	209	366	-	-	0	0	0	46	300	623	2,448
Week Average Usage [b] (ft^2-hrs)	108	186	268	-	-	0	0	4.5	70	248	535	1,260
Test Day / Week Average Usage Ratio	108	1.1	1.0	-	-	0	0	0.4	1.0	1.3	2.0	7.0
Log/Logger Ratio Week Average	136	1.7	6.6	0.9	2.3	0.04	0.5	0.9	1.0	1.0	1.5	74
Garage Door												
Test Day 24 hr Usage [a] (ft^2-hrs)	105	0.31	0.9	0.07	4.4	0.003	0.02	0.03	0.06	0.15	0.57	6.2
Week Average Usage [b] (ft^2-hrs)	105	0.39	1.1	0.10	4.3	0.004	0.02	0.04	0.07	0.22	0.62	8.0
Test Day / Week Average Usage Ratio	105	1.1	1.0	0.8	2.7	0.01	0.22	0.52	0.85	1.3	2.5	6.1

No Window/Door Usage	N	Number of Homes with No Window/Door Usage	% No Window/Door Usage
Test Day [a]	108	34	32
Preceding Week [b]	108	16	15

a) Test day usage: is measured during the 24-hour air testing day.
b) Preceding week usage: measured during the one-week usage preceding the 24-hour Test Day.

Table 26. Percentage comparisons of actual measured home window/door usage and the homeowner's estimated seasonal usage in the UCB mail survey.

Percentage Comparisons of Measured and Estimated Window/Door Usage			
	Home-Dates [a]	N	Percentage of Homes (%)
Zero measured usage and zero estimated usage	48	7	15
Measured usage and zero estimated	48	5	10
Measured usage within [b] estimated usage range	48	7	15
Measured usage higher [c] than high end estimated usage	48	25	52
Measured usage lower [d] than low end estimated usage	48	4	8.3

a) Home-Dates: Total of 48 home seasonal measurement dates in 26 homes.
b) The actual measured week average usage is within the range of the homeowner estimated usage from the UCB mail survey for that season and homes with non-zero usage.
c) The actual measured week average usage is larger than the high end of the homeowner estimated usage from the UCB mail survey for that season.
d) The actual measured week average usage is lower than the low end of the homeowner estimated usage from the UCB mail survey for that season.

Table 27. Differences between the actual measured home window/door usage and the homeowner's estimated seasonal usage in the UCB mail survey.

Differences Between Measured and Estimated Window/Door Usage												
Compound	N	Mean	Standard Deviation	Geometric Mean	Geometric Standard Deviation	Min	10%	25%	50%	75%	90%	Max
Measured usage in homes with zero estimated usage (ft^2-hrs)	5	33	67	4.4	10.5	0.3	0.3	1.1	3.1	9.6	153	153
Measured [a] usage above high end estimated usage ratio	25	48	209	4.1	4.7	1.0	1.2	1.5	3.1	6.3	18	1,050
Measured [b] usage below low end estimated usage ratio	4	0.2	0.2	-	-	0.0	0.0	0.02	0.04	0.3	0.5	0.5

a) Ratio of the actual measured week average usage to the high end estimated usage in homes with higher actual usage than estimated usage for that season.
b) Ratio of the actual measured week average usage to the low end estimated usage in homes with lower actual usage than estimated usage for that season.

Table 28. Mechanical system usage for the 24-hour Test Day period and the ratio of the Test Day usage to the week average usage.

Mechanical System Usage (hours)												
Variable	N	Mean	Standard Dev.	Geometric Mean	Geometric Std. Dev.	Min	10%	25%	50%	75%	90%	Max
Test Day Usage [a]												
Kitchen Exhaust	108	0.2	0.5	-	-	0	0	0	0	0	0.8	3.6
Bathroom Exhaust	105	0.7	1.4	-	-	0	0	0	0.05	0.7	1.9	7.5
Other Exhaust (i.e., dryer, laundry)	108	1.2	2.2	-	-	0	0	0	0.3	1.5	3.5	17
Ducted Outdoor Air (DOA)	14	4.3	4.8	2.2	3.9	0.1	0.4	1.5	2.5	6.1	9.7	18
Heat Recovery Ventilator (HRV)	8	21	6.1	20	1.5	7.8	13	22	24	24	24	24
Whole House Fan (WHF)	5	3.4	4.9	-	-	0	0	0	0.7	4.8	11	11
FAU with Return Air Damper (RAD)	6	6.5	7.3	-	-	0	0	0	5.3	12.8	16	16
Forced Air Unit #1	108	3.2	5.6	-	-	0	0	0	1.1	3.6	9.7	24
Test Day/Week Average [b] Usage Ratio												
Kitchen Exhaust	108	1.4	1.9	-	-	0	0	0.5	1.0	1.0	5.0	7.0
Bathroom Exhaust	105	1.4	1.9	-	-	0	0	0.3	1.0	1.3	4.0	7.0
Other Exhaust (i.e., dryer, laundry)	108	1.3	1.6	-	-	0	0	0	0.9	1.8	3.4	7.0
Ducted Outdoor Air (DOA)	14	1.7	1.8	1.0	3.1	0.09	0.13	0.9	1.1	1.7	3.6	7.0
Heat Recovery Ventilator (HRV)	8	1.0	0.04	1.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0
Whole House Fan (WHF)	5	0.6	0.4	-	-	0	0	0.5	0.7	1.0	1.0	1.0
FAU with Return Air Damper (RAD)	6	1.0	0.1	1.0	1.1	0.9	0.9	1.0	1.0	1.2	1.2	1.2
Forced Air Unit #1	108	1.2	1.5	-	-	0	0	0.1	0.9	1.2	2.5	7.0

a) Hours of usage during the 24-hour Test Day period.
b) Ratio of the hours of usage during the 24-hour Test Day to the average 24-hour usage measured during the previous week.

Table 29. Mechanical outdoor air ventilation system characteristics and code requirements.

Outdoor Air Exchange Rate Code Requirement Variables										
Variable	N	Min	10%	25%	50%	75%	90%	Max	% Homes Fail [d] ASHRAE 62.2 - 2004 Guidelines	% Homes Fail [e] Title 24 ACM - 2001 Requirements
Ducted Outdoor Air Systems (DOA) [a]										
- 24 hr average outdoor airflow rate (ach) [b]	14	0.002	0.002	0.002	0.01	0.03	0.07	0.08		
- 24 hr average fan ON time (%) [b]	14	0.6	1.6	6.4	10	25	35	74		
- Outdoor airflow rate (cfm)	14	8.8	14	27	38	51	68	355	64	86
Title 24 ACM - 2001 requirements (cfm)	14	60	64	79	90	102	152	172		
ASHRAE 62.2 guidelines (cfm)	14	35	36	40	49	55	75	82		
Heat Recovery Ventilators, (HRV) [c]										
- 24 hr average outdoor airflow rate (ach) [b]	8	0.12	0.17	0.22	0.30	0.44	0.45	0.47		
- 24 hr average fan ON time (%) [b]	8	32	55	90	100	100	100	100		
- Outdoor airflow rate (cfm)	8	66	83	113	128	150	155	159	0	22
Title 24 ACM - 2001 requirements (cfm)	8	81	83	93	107	116	124	134		
ASHRAE 62.2 guidelines (cfm)	8	40	45	50	54	61	64	66		

a) DOA systems not disabled during the 24-hour Test Day.
b) Mechanically provided outdoor air exchange rate measured during the 24-hour Test Day.
c) HRV systems not disabled during the 24-hour Test Day.
d) ASHRAE 62.2-2004 requirement: 0.01 cfm/ft^2 floor area + 15 cfm times (#bedrooms +1)
e) California Title 24 ACM-2001 requirement: 0.047 cfm/ft^2 floor area for homes built with an intended envelope air tightness of SLA less than 3.0.

Table 30. PFT measurements of outdoor air exchange rates for the 24-hour Test Day and the following two-week period.

PFT Measurement of Outdoor Air Exchange Rates

	N	Mean	Standard Deviation	Geometric Mean	Geometric Std. Dev.	Min	10%	25%	50%	75%	90%	Max	CBC Code [a] Requirement
24-Hour Measurement (ach)	107 [b]	0.48	0.78	0.31	2.24	0.09	0.13	0.18	0.26	0.45	0.85	5.3	0.35
2-Week Measurement (ach)	21 [b]	0.45	0.54	0.31	2.23	0.11	0.14	0.19	0.24	0.42	0.83	2.3	0.35
24-Hour vs. 2-Week													
- Absolute difference [c]	35 [b]	0.49	1.13	0.08	6.99	0.001	0.01	0.03	0.07	0.30	1.7	5.1	na
- Relative Difference [d]	35 [b]	0.32	0.31	0.16	3.92	0.01	0.02	0.06	0.19	0.58	0.84	1.1	na

a) 2001 California Building Code (CBC), Appendix Chapter 12, Interior Environment, Division 1-Ventilation, Table A-12-A, Outdoor Air requirements for Ventilation, Living Areas.
b) 107 homes, in the All Homes Sample Frame, with 24-hour PFT measurements. 21 homes in the All Homes Sample Frame with 2-week measurements and 35 homes for all homes tested with both 24-hour and 2-week measurements.
c) Absolute difference is calculated as the absolute difference between the 24-hour and two-week samples.
d) Relative difference is calculated as the relative standard deviation of a 24-hour and two-week samples.

Table 31. Comparison of outdoor air exchange rate PFT measurements to CBC 2001 minimum code requirements.

Comparison of Outdoor Exchange Rate PFT Measurements to CBC 2001 Minimum Code Requirements														
	Ratio of outdoor air exchange rate to CBC 2001 minimum codes requirements for homes below code requirements													
	N	Mean	Standard Deviation	Geometric Mean	Geometric Standard Deviation	Min	10%	25%	50%	75%	90%	Max	% < CBC Code Requirement	CBC Code [a] Requirement
24-Hour Measurement (ach)	72	0.61	0.21	0.57	1.5	0.25	0.31	0.46	0.58	0.75	0.92	1.0	67	0.35

a) 2001 California Building Code (CBC), Appendix Chapter 12, Interior Environment, Division 1-Ventilation, Table A-12-A, Outdoor Air Requirements for Ventilation, Living Areas.

Table 32. Percentage of samples with concentrations of volatile organic compounds greater than the method detection limit concentration.

Percent of Samples with Concentrations of Volatile Organic Compounds Greater than the Method Detection Limit Concentration

Compound	N Indoor/ Outdoor	MDL Mass [a] (ng)	MDL Concentration [b] (ug/m^3)	Indoor Air Guideline (ug/m^3)	Ratio of MDL Concentration to Guideline	%> MDL Concentration Indoor Air	%> MDL Concentration Outdoor Air
Acetaldehyde	105/ 39	9.0	0.30	9[c]	3E-2	100	97
Benzene	107/ 40	3.5	0.25	60[c]	4E-3	73	55
2-Butoxyethanol	107/ 40	1.9	0.13	3,000[d]	4E-5	86	10
Caprolactam	107/ 40	3.4	0.24	500[d]	5E-4	0	3
1,4-Dichlorobenzene	107/ 40	2.9	0.21	800[c]	3E-4	29	8
Ethylene glycol	107/ 40	16.4	1.17	400[c]	3E-3	56	0
Formaldehyde	105/ 39	9.0	0.30	33[e]	9E-3	100	97
Hexanal	107/ 40	1.4	0.10	na	na	99	60
n-Hexane	107/ 40	4.2	0.30	7,000[c]	4E-5	80	40
d-Limonene	107/ 40	4.2	0.30	na	na	93	15
1-Methyl-2-pyrrolidinone	107/ 40	6.0	0.43	2,000[d]	2E-4	13	0
Naphthalene	107/ 40	2.0	0.14	9[c]	2E-2	82	25
Phenol	107/ 40	2.8	0.20	200[c]	1E-3	100	98
alpha-Pinene	107/ 40	3.0	0.22	2,800[d]	1E-4	99	8
Styrene	107/ 40	3.1	0.22	900[c]	2E-4	93	38
Tetrachloroethene	107/ 40	4.7	0.33	35[c]	1E-2	27	10
Toluene	107/ 40	4.9	0.35	300[c]	1E-3	100	88
Trichloromethane	107/ 40	4.9	0.35	300[c]	1E-3	42	0
1,2,4-Trimethylbenzene	107/ 40	3.3	0.24	3,125[d]	1E-4	87	63
Vinyl acetate	107/ 40	5.6	0.40	200[c]	2E-3	2	0
m,p-Xylene	107/ 40	3.8	0.27	700[c]	4E-4	97	90
o-Xylene	107/ 40	3.2	0.23	700[c]	3E-4	91	63

a) MDL mass = Method mass detection limit for GS/MS VOC analysis and HPLC formaldehyde and acetaldehyde analyses.
b) MDL concentration = Method concentration detection limit for typical air sample volumes; 14 L for VOCs and 30 L for formaldehyde and acetaldehyde.
c) OEHHA Chronic Reference Exposure Levels (OEHHA 2003).
d) 1/40th of the 8-hour occupational health guideline in µg/m^3 (e.g., Cal/OSHA PELs, ACGIH TLVs, DFG MAKs).
e) Formaldehyde – California Air Resources Board Indoor Air Quality Guideline, 2005. na = no available guideline.

Table 33. Concentrations of individual volatile organic compounds measured indoors over the 24-hour Test Day.

Indoor Concentrations of Volatile Organic Compounds ($\mu g/m^3$)

Compound	N	Mean	Standard Dev.	Geometric Mean	Geometric Std. Dev.	Min	10%	25%	50%	75%	90%	Max	Indoor Guideline
Acetaldehyde	105	25	20	19	2.3	1.9	6.3	12	20	32	55	102	9[a]
Benzene	107	1.6	2.2	0.8	3.8	0.1	0.1	0.1	1.1	2.0	4.3	15	60[a]
2-Butoxyethanol	107	7.3	19	2.0	6.0	0.1	0.2	0.9	2.8	6.0	14	180	3,000[b]
Caprolactam	107	0.1	0.01	0.1	1.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	500[b]
1,4-Dichlorobenzene	107	5.2	27	0.2	5.0	0.1	0.1	0.1	0.1	0.2	1.7	219	800[a]
Ethylene glycol	107	12	20	3.2	5.6	0.5	0.6	0.6	3.2	16	36	120	400[a]
Formaldehyde	105	43	27	36	1.9	4.8	14	25	36	58	86	136	33[c]
Hexanal	107	10	7.9	7.0	2.7	0.1	2.3	4.1	7.6	14	22	35	na
n-Hexane	107	2.3	3.9	0.9	3.8	0.1	0.2	0.3	0.8	2.5	5.2	24	7,000[a]
d-Limonene	107	18	25	7.6	5.0	0.1	0.9	3.5	11	21	37	152	na
1-Methyl-2-pyrrolidinone	107	0.4	0.8	0.3	1.7	0.2	0.2	0.2	0.2	0.2	0.4	8.3	2,000[b]
Naphthalene	107	0.3	0.5	0.2	2.3	0.1	0.1	0.1	0.2	0.3	0.6	4.9	9[a]
Phenol	107	2.0	1.3	1.6	2.0	0.2	0.6	1.1	1.7	2.6	3.9	6.5	200[a]
alpha-Pinene	107	15	13	9.3	3.3	0.1	1.9	6.6	11	20	33	65	2,800[b]
Styrene	107	1.8	6.0	0.9	2.8	0.1	0.2	0.6	0.9	1.8	2.8	62	900[a]
Tetrachloroethene	107	0.6	2.3	0.3	2.4	0.1	0.2	0.2	0.2	0.3	0.6	23	35[a]
Toluene	107	17	22	9.5	2.9	0.3	3.0	4.8	8.5	18	42	115	300[a]
Trichloromethane	107	0.7	1.4	0.4	2.8	0.1	0.2	0.2	0.2	0.7	1.8	12	300[a]
1,2,4-Trimethylbenzene	107	1.8	2.0	1.0	3.2	0.1	0.1	0.6	1.1	2.3	3.8	13	3,125[b]
Vinyl acetate	107	0.2	0.02	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.3	200[a]
m,p-Xylene	107	7.1	8.4	4.2	3.1	0.1	1.4	2.3	4.2	9.2	15	60	700[a]
o-Xylene	107	2.1	2.7	1.1	3.3	0.1	0.1	0.6	1.2	2.7	4.7	20	700[a]

a) OEHHA Chronic Reference Exposure Levels (OEHHA 2003).
b) 1/40th of the 8-hour occupational health guideline in $\mu g/m^3$ (e.g., Cal/OSHA PELs, ACGIH TLVs, DFG MAKs).
c) Formaldehyde – California Air Resources Board Indoor Air Quality Guideline, 2005. na = no available guideline.

Table 34. Concentration of individual volatile organic compounds measured outdoors over the 24-hour Test Day.

Outdoor Concentrations of Volatile Organic Compounds (μg/m^3)

Compound	N	Mean	Standard Deviation	Geometric Mean	Geometric Std. Dev.	Min	10%	25%	50%	75%	90%	Max	Indoor Guideline
Acetaldehyde	39	2.1	1.4	1.5	2.6	0.2	0.3	1.0	2.2	3.3	4.0	5.0	9[a]
Benzene	40	0.5	0.5	0.3	2.6	0.1	0.1	0.1	0.3	0.7	1.2	2.1	60[a]
2-Butoxyethanol	40	0.1	0.2	0.1	1.9	0.1	0.1	0.1	0.1	0.1	0.1	0.8	3,000[b]
Caprolactam	40	0.1	0.04	0.1	1.2	0.1	0.1	0.1	0.1	0.1	0.1	0.3	500[b]
1,4-Dichlorobenzene	40	0.1	0.1	0.1	1.3	0.1	0.1	0.1	0.1	0.1	0.1	0.4	800[a]
Ethylene glycol	40	0.6	0.03	0.6	1.1	0.5	0.6	0.6	0.6	0.6	0.6	0.7	400[a]
Formaldehyde	39	2.2	1.4	1.8	2.1	0.2	0.7	1.2	2.1	2.9	3.5	8.0	33[c]
Hexanal	40	0.2	0.2	0.2	2.7	0.1	0.1	0.1	0.2	0.4	0.5	0.7	na
n-Hexane	40	0.3	0.3	0.2	2	0.1	0.2	0.2	0.2	0.3	0.9	1.1	7,000[a]
d-Limonene	40	0.2	0.2	0.2	1.7	0.1	0.1	0.2	0.2	0.2	0.4	1.5	na
1-Methyl-2-pyrrolidinone	40	0.2	0.01	0.2	1.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	2,000[b]
Naphthalene	40	0.1	0.03	0.1	1.4	0.1	0.1	0.1	0.1	0.1	0.1	0.2	9[a]
Phenol	40	0.6	0.3	0.5	2.1	0.02	0.2	0.4	0.5	0.7	0.9	1.6	200[a]
alpha-Pinene	40	0.1	0.04	0.1	1.2	0.1	0.1	0.1	0.1	0.1	0.1	0.3	2,800[b]
Styrene	40	0.2	0.2	0.1	1.8	0.03	0.1	0.1	0.1	0.2	0.3	0.7	900[a]
Tetrachloroethene	40	0.2	0.1	0.2	1.3	0.1	0.2	0.2	0.2	0.2	0.2	0.4	35[a]
Toluene	40	1.7	1.4	1.2	2.6	0.2	0.2	0.8	1.2	2.2	4.0	6.3	300[a]
Trichloromethane	40	0.2	0.01	0.2	1.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	300[a]
1,2,4-Trimethylbenzene	40	0.4	0.3	0.3	2.2	0.1	0.1	0.1	0.2	0.6	0.8	1.0	3,125[b]
Vinyl acetate	40	0.2	0.01	0.2	1.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	200[a]
m,p-Xylene	40	1.2	0.9	0.9	2.5	0.1	0.2	0.5	1.0	2.0	2.5	3.3	700[a]
o-Xylene	40	0.3	0.3	0.2	2.2	0.1	0.1	0.1	0.2	0.5	0.8	1.1	700[a]

a) OEHHA Chronic Reference Exposure Levels (OEHHA 2003).
b) 1/40th of the 8-hour occupational health guideline in μg/m^3 (e.g., Cal/OSHA PELs, ACGIH TLVs, DFG MAKs).
c) Formaldehyde – California Air Resources Board Indoor Air Quality Guideline, 2005. na = no available guideline.

Table 35. Maximum indoor concentrations of the volatile organic compounds comparison to indoor air contaminant guidelines.

Maximum Indoor Concentrations of Volatile Organic Compounds Comparison to the Indoor Guidelines (μg/m^3)

Compound	Maximum Concentration (μg/m^3)	Indoor Guideline (μg/m^3)	Maximum Concentration to Indoor Guideline Ratio
Tetrachloroethene	22.6	35 [a]	0.646
Naphthalene	4.9	9 [a]	0.544
Toluene	115.2	300 [a]	0.384
Ethylene glycol	119.5	400 [a]	0.299
1,4-Dichlorobenzene	219	800 [a]	0.274
Benzene	15.1	60 [a]	0.252
m,p-Xylene	60.3	700 [a]	0.086
Styrene	62	900 [a]	0.069
2-Butoxyethanol	179.7	3,000 [b]	0.060
Trichloromethane	11.8	300 [a]	0.039
Phenol	6.5	200 [a]	0.033
o-Xylene	19.9	700 [a]	0.028
alpha-Pinene	65.1	2,800 [b]	0.023
1,2,4-Trimethylbenzene	13.2	3,125 [b]	0.004
1-Methyl-2-pyrrolidinone	8.3	2,000 [b]	0.004
n-Hexane	24	7,000 [a]	0.003
Vinyl acetate	0.3	200 [a]	0.002
Caprolactam	0.1	500 [b]	<0.0001
Hexanal	35.1	na	na
d-Limonene	152.3	na	na

a) OEHHA Chronic Reference Exposure Levels (OEHHA 2003).
b) 1/40th of the 8-hour occupational health guideline in μg/m^3 (e.g., Cal/OSHA PELs, ACGIH TLVs, DFG MAKs). na = no available guideline.

Table 36. Comparison of indoor concentrations of formaldehyde and acetaldehyde to indoor air contaminant guidelines.

Comparison of Indoor Concentrations of Formaldehyde and Acetaldehyde to Indoor Air Contaminant Guidelines [a]														
Compound	N	Mean	Standard Deviation	Geometric Mean	Geometric Standard Deviation	Min	10%	25%	50%	75%	90%	Max	% > Indoor Air Guideline	Indoor Air Guideline (µg/m^3)
Acetaldehyde														
Chronic Reference Exposure Level	86	3.3	2.2	2.8	1.8	1.2	1.4	1.7	2.5	4.0	6.5	11	82	9[b]
Formaldehyde														
Chronic Reference Exposure Level	105	15	9.2	12	1.9	1.6	4.8	8.2	12	19	29	45	100	3[b]
ARB Indoor Air Guideline	62	1.8	0.8	1.7	1.5	1.0	1.1	1.2	1.5	2.1	2.9	4.1	59	33[c]
Acute Reference Exposure Level	7	1.2	0.2	1.2	1.1	1.0	1.0	1.1	1.2	1.3	1.4	1.4	6.7	94[d]

a) Ratio of indoor concentration to indoor air contaminant guidelines for homes exceeding the guideline.
b) OEHHA Chronic Reference Exposure Levels (OEHHA 2003).
c) Formaldehyde – California Air Resources Board Indoor Air Quality Guideline, 2005; OEHHA Interim 8-hour Reference Exposure Level.
d) OEHHA Acute Reference Exposure Levels (OEHHA 2000).

Table 37. Percentage of homes with indoor and concentrations of carbon monoxide, nitrogen dioxide, and $PM_{2.5}$ particulate matter greater than the method detection limit.

Percent of Concentrations of Carbon Monoxide, Nitrogen Dioxide, and $PM_{2.5}$ Particulate Matter Greater than the Method Detection Limit ($\mu g/m^3$)

Compound	N Indoor/ Outdoor	MDL Mass [a] (µg)	MDL [b] Concentration	Indoor [c] Guideline	Ratio of MDL/Guideline	% > MDL for Indoor Air	%> MDL for Outdoor Air
Carbon Monoxide (ppm)	107/ 40	na	0.8	9	0.09	100	100
Nitrogen Dioxide ($\mu g/m^3$)	29/ 11	0.8	5.7	150	0.04	48	9
$PM_{2.5}$ Particulate Matter ($\mu g/m^3$)	29/ 11	5	1.8	65	0.03	100	100

a) MDL Mass = Method mass detection limit for nitrogen dioxide spectrophotometer analysis and $PM_{2.5}$ particulate matter gravimetrical analysis. Not applicable for real-time carbon monoxide measurements.
b) MDL Concentration = Method detection limit for a typical volume; NO_2 = 0.14 m^3 and $PM_{2.5}$ = 2.8 m^3; CO MDL concentration determined from analyses of the variance of the average concentration from 8 co-located IAQ-Calc instruments.
c) California Air Resources Board Indoor Air Quality Guideline, 2005: Carbon monoxide (8-hr), Nitrogen dioxide (24-hr), $PM_{2.5}$ Particulate matter (24 hr).

Table 38. Concentrations of carbon monoxide, nitrogen dioxide and $PM_{2.5}$ particulate matter measured indoor and outdoor over the 24-hour Test Day.

Concentrations of Carbon Monoxide, Nitrogen Dioxide and $PM_{2.5}$ Particulate Matter

Compound	N	Mean	Standard Deviation	Geometric Mean	Geometric Standard Deviation	Min	10%	25%	50%	75%	90%	Max	Indoor Guideline [a]
Indoor													
Carbon Monoxide (ppm) - 24-hour average	105	0.9	0.6	0.8	1.9	0.4	0.4	0.4	0.8	1.4	1.8	2.4	na
- 8 hour average maximum	105	1.2	0.7	0.7	7.4	0.4	0.4	0.4	1.1	1.8	2.1	3.7	9
- 1 hour average maximum	105	1.6	1.1	1.0	7.8	0.4	0.4	0.4	1.6	2.3	2.8	6.8	20
Nitrogen Dioxide ($\mu g/m^3$)	29	9.8	11	6.2	2.5	2.6	2.7	2.8	3.1	13	23	50	150
Particulate Matter $PM_{2.5}$ ($\mu g/m^3$)	28	13	9.0	11	1.8	3.8	6.0	8.2	11	14	31	36	65
Outdoor													
Carbon Monoxide (ppm) - 24-hour average	39	1.4	0.9	1.1	2.2	0.4	0.4	0.4	1.2	2.1	2.8	3.6	na
- 8 hour average maximum	39	1.9	1.2	1.5	2.3	0.4	0.4	0.4	1.9	2.7	3.6	4.4	9
- 1 hour average maximum	39	2.3	1.2	1.9	2.1	0.4	0.4	1.3	2.4	3.2	3.8	4.9	20
Nitrogen Dioxide ($\mu g/m^3$)	11	3.9	3.4	3.4	1.6	2.7	2.7	2.8	2.9	3.1	3.2	14	150
Particulate Matter $PM_{2.5}$ ($\mu g/m^3$)	11	7.9	2.5	7.5	1.4	4.3	5.0	5.3	8.7	9.5	10	12	65

a) California Air Resources Board Indoor Air Quality Guidelines, 2005: Carbon monoxide (1-hr and 8-hr), Nitrogen dioxide (24-hr), $PM_{2.5}$ Particulate Matter (24-hr). There is no 24-hour exposure guideline for carbon monoxide.

Table 39. Temperature, relative humidity, and carbon dioxide concentrations measured indoors and outdoors over the 24-hour Test Day.

Temperature, Relative Humidity and Carbon Dioxide Concentrations

Compound	N	Mean	Standard Deviation	Geometric Mean	Geometric Standard Dev.	Min	10%	25%	50%	75%	90%	Max
Indoor												
Carbon Dioxide (ppm) [a] - 24-hour average	107	610	177	587	1.3	334	405	469	564	723	890	1108
Temperature (°F) - 24-hour average	103	72.4	5.0	72.2	1.1	62.7	65.7	68.1	72.3	76.6	78.7	82.8
Relative Humidity (%) - 24-hour average	103	43.4	9.6	42.2	1.3	19.5	29.7	37.5	45.2	49.7	54.0	63.5
Outdoor												
Carbon Dioxide (ppm) [b] - 24-hour average	39	326	23	325	1.1	258	298	315	323	339	354	369
Temperature (°F) - 24-hour average	39	62.4	10.4	61.6	1.2	44.9	48.1	52.5	63.8	71.1	75.6	82.4
Relative Humidity (%) - 24-hour average	39	57.0	18.6	53.8	1.4	25.1	31.7	39.2	57.9	72.8	80.6	93.3

a) Carbon dioxide concentration guideline; ASHRAE 62.1-2004, 700 ppm greater than outdoors – for acceptable body odor.
b) There appears to be a temperature induced error associated with the outdoor carbon dioxide measurements that results in the measured concentration being substantially lower than the true concentration.

Table 40. Comparison of volatile organic compound concentrations measured in new residences in this study and two other studies.

Comparison of Indoor Concentrations of Volatile Organic Compounds in New Homes

	This Study [a] GM Mean	Other Studies [b] GM Mean	Ratio [c]	This Study [a] Maximum	Other Studies [b] Maximum	Ratio [d]
Acetaldehyde	19	14	1.4	102	43	2.4
Benzene	2.2	0.5	4.4	15	6.1	2.5
2-Butoxyethanol	2	2.9	0.7	180	12	15
Ethylene glycol	3.2	48	0.1	120	490	0.2
Formaldehyde	36	32	1.1	136	62	2.2
Hexanal	7	15	0.5	35	36	1.0
d-Limonene	7.6	4.3	1.8	152	12	13
Phenol	1.6	1.8	0.9	6.5	5.8	1.1
alpha-Pinene	9.3	23	0.4	65	60	1.1
Toluene	9.5	8.5	1.1	115	68	1.7
Trichloromethane	0.4	0.1	4.0	12	0.5	24
m,p-Xylene	4.2	2.1	2.0	60	11	5.5
o-Xylene	1.1	0.6	1.8	20	4.4	4.5

a) Geometric mean and maximum indoor concentrations in the new Californian homes in this study (n=107 except for formaldehyde and acetaldehyde with n=105)

b) Geometric mean and maximum concentrations of 20 new homes in two other studies as reported in Volatile Organic Compounds in Indoor Air: A Review of Concentrations Measured Since 1990 (Hodgson and Levin 2003). 6 experimental low-emitting and 3 conventional homes, Denver, Colorado, 1992–1993, and 4 manufactured and 7 site-built homes, east and southeast United States, 1997–1998.

c) Ratio of geometric mean in this study to geometric mean in two other studies.

d) Ratio of maximum in this study to maximum in two other studies.

Table 41. Percentage of homes with concentrations exceeding California Proposition 65 Safe Harbor Dose concentrations.

California Proposition 65 Safe Harbor Dose Indoor Concentrations [a]

Compound	Number of Home Measurements	NSRL Concentration (µg/m^3)	Percentage of Homes Exceeding the NSRL Concentration (%)	MADL Concentration (µg/m^3)	Percentage of Homes Exceeding the MADL Concentration (%)
Acetaldehyde	105	4.5	93	NA	NA
Benzene	107	0.7	63	2.5	20
1,4-Dichlorobenzene	107	1.0	12	NA	NA
Formaldehyde	105	2.0	100	NA	NA
Naphthalene	107	0.3	27	NA	NA
Tetrachloroethene	107	0.7	8	NA	NA
Toluene	107	NA	NA	350	0
Trichloromethane	107	2.0	8	NA	NA

a) California Proposition 65 Safe Harbor Dose indoor concentrations calculated from the No Significant Risk Level (NSRL) for carcinogens and the Maximum Allowable Dose Level (MADL) assuming continuous 24-hour exposure with a total daily inhaled air volume of 20 m^3 and 100% absorption by the respiratory system.

NA = no available Safe Harbor Dose.

Table 42. Occupant cooking and cleaning source activities conducted during the 24-hour Test Day.

Cooking and Cleaning Source Activities (minutes)													
	Activity	N	Mean	Standard Deviation	Geometric Mean	Geometric Std. Dev.	min	10%	25%	50%	75%	90%	Max
Cooking Activities	Toasting	50	6.4	5.2	4.9	2.1	1	2	3	5	8	15	24
	Frying or Sautéing	36	24	25	16	2.7	1	5	10	17	30	77	90
	Baking	33	46	34	36	2.0	10	15	21	45	60	90	180
	Broiling	11	39	45	22	3.2	5	6	6	19	65	80	150
	Warming/Boiling Water Soup, etc.	47	30	30	19	2.6	3	6	8	20	35	70	135
	Microwave	79	6.7	6.1	4.1	3.1	0.2	1	2	4	10	15	23
	Other	8	22	19	17	2.3	4	4	11	16	32	60	60
	Total Cooking Activities	97	52	56	29	3.5	0.3	5	16	35	65	126	295
Cleaning Activities	Vacuuming	16	49	76	25	3.0	7	9	10	25	48	145	300
	Sweeping or Dusting	16	24	33	13	3.1	3	3	6	12	20	75	120
	Use of Dishwasher	38	76	51	56	2.7	2	20	40	68	90	180	240
	Use of Clothes Washer	44	95	88	69	2.2	15	30	41	59	118	210	390
	Use of Furniture Polish	5	27	36	16	3.0	5	5	10	10	20	90	90
	Use of cleaning chemicals	24	21	39	9	3.5	1	2	5	10	15	40	180
	Other	1	10	-	10	-	10	10	10	10	10	10	10
	Total Cleaning Activities	74	120	126	66	3.8	1	10	45	83	152	260	800

Table 43. Occupant special activities, garage and outdoor source activities conducted during the 24-hour Test Day.

Occupant Special, Garage, and Outdoor Source Activities (minutes)													
	Activity	N	Mean	Standard Deviation	Geometric Mean	Geometric Std. Dev.	Min	10%	25%	50%	75%	90%	Max
Occupant Special Activities	Gas burning fireplace	1	140	-	140	-	140	140	140	140	140	140	140
	Candle burning	4	203	108	185	1.6	120	120	135	165	270	360	360
	Painting	1	28	-	28	-	28	28	28	28	28	28	28
	Pesticide application	3	482	829	24	35	2	2	2	5	1,440	1,440	1,440
	Nail polish application or removal	3	3.3	1.5	3.1	1.6	2	2	2	3	5	5	5
	Aerosol air fresheners	6	0.6	0.5	0.3	4.8	0.0	0.0	0.1	0.7	1	1	1
	Aerosol personal care products	24	1.9	4.0	0.7	4.0	0.0	0.1	0.4	1	2	3	20
	Showering or bathing	80	33	18	28	1.8	5	13	20	30	42	58	85
	Large party/dinner gatherings	3	90	52	76	2.2	30	30	30	120	120	120	120
	Nobody at home	44	347	255	251	2.5	10	90	150	308	460	645	1,170
	Other activities: dust, smoke, or fumes	3	28	18	24	2.2	10	10	10	30	45	45	45
	Total Special Activities – excluding "nobody at home"	84	65	169	32	2.9	0.3	13	20	30	49	90	1,450
Garage Activities	Vehicle operated in garage (vehicle-minutes)	39	2.7	2.2	1.9	2.5	0.2	0.5	1.0	2.0	4.0	5.0	10
	Vehicle storage in garage (vehicle-minutes)	62	1,338	767	994	3.0	5.0	360	730	1,440	1,860	2,400	3,480
	Total Vehicle Activities	72	1,134	860	381	12.3	0.3	3	447	1,037	1,562	2,400	3,480
Outdoor Activities	Use of gasoline powered equipment	4	31	20	27	1.8	15	15	18	25	45	60	60
	Painting	1	55	-	55	-	55	55	55	55	55	55	55
	Barbecuing	8	32	18	28	1.7	15	15	20	24	48	60	60
	Smoking outdoors	7	78	106	36	4.0	5	5	14	25	120	300	300
	Other activities: dust, smoke, or fumes	1	1.0	-	1.0	-	1	1	1	1	1	1	1
	Total Outdoor Activities	18	53	81	28	3.5	1	5	19	29	60	120	360

Table 44. Homeowner reported IAQ related perceptions and observations.

Homeowner Reported IAQ Related Perceptions and Observations		
Variable	N [a]	%
During the past three weeks have you experienced any of the following physical symptoms when in your home that you do not experience when you are away from the home?		
One or more of the symptoms below	108	28
Eye irritation	108	11
Nose/sinus congestion	108	19
Nose irritation	108	12
Allergy symptoms	108	15
Headache	108	13
Skin irritation	108	5.6
Difficulty concentrating	108	6.5
Asthma symptoms	108	4.6
Other	108	3.7
During the past week, please indicate if you have noticed a significant period when your home has experienced each of the conditions listed below.		
Too hot	108	19
Too cold	108	15
Too dry	108	8.3
Too humid	108	1.9
Too drafty	108	0.0
Too stagnant (not enough air movement)	108	12
Too dusty	108	11
During the past week, please indicate if you have noticed, seen, or smelled mold or mildew in the following locations?		
Bathrooms	108	13
Basement or crawlspace	108	0.9
Walls or ceilings	108	1.9
Carpets	108	0.9
Closets	108	0.9
Cabinetry	108	1.9
Other	108	2.8
Has anyone in your household had a medical diagnosis of any of the following?		
Allergies	108	36
Asthma	108	16
Chemical sensitivity	108	3.7
Other activity-limiting conditions	108	4.6

a) Number of homes with completed questionnaires.

Table 45. Indoor emission rates of volatile organic compounds over the 24-hour Test Day.

Indoor Emission Rates of Volatile Organic Compounds (μg/m^3-h) [a]												
Compound	N	Mean	Standard Deviation	Geometric Mean	Geometric Standard Deviation	Min	10%	25%	50%	75%	90%	Max
Acetaldehyde	99	5.7	3.2	4.9	1.8	1.2	2.1	3.7	5.3	7.0	9.1	20
Benzene	77	0.4	0.6	-	-	-0.4	0.01	0.06	0.2	0.5	1.0	4.3
2-Butoxyethanol	91	2.0	3.7	1.0	3.5	0.03	0.2	0.4	0.9	2.4	4.0	32
Caprolactam	3	-0.03	0.02	-	-	-0.06	-0.06	-0.06	-0.03	-0.01	-0.01	-0.01
1,4-Dichlorobenzene	35	7.4	26	-	-	-0.3	-0.09	0.01	0.1	0.6	15	139
Ethylene glycol	59	6.7	8.5	3.7	3.4	0.05	1.0	1.8	3.9	7.8	14	44
Formaldehyde	99	13	10	10	2.0	2.3	4.0	5.8	11	16	23	65
Hexanal	105	2.5	1.4	2.1	1.8	0.4	0.9	1.5	2.2	3.3	4.6	6.6
n-Hexane	87	0.6	1.1	-	-	-0.2	0.02	0.1	0.2	0.5	1.9	7.0
d-Limonene	100	3.9	4.1	-	-	-4.2	0.6	1.4	2.6	4.8	10	20
1-Methyl-2-pyrrolidinone	13	0.3	0.5	0.1	5.2	0.00	0.02	0.07	0.1	0.4	1.0	1.7
Naphthalene	87	0.07	0.2	-	-	-0.01	0.01	0.01	0.03	0.06	0.1	1.5
Phenol	105	0.4	0.5	-	-	-0.5	0.02	0.1	0.3	0.5	0.9	2.5
alpha-Pinene	104	3.6	2.2	2.9	2.3	0.01	1.3	2.2	2.9	4.5	6.5	10
Styrene	99	0.4	1.1	-	-	-0.4	0.07	0.2	0.2	0.4	0.7	10
Tetrachloroethene	31	0.4	1.0	-	-	-0.05	-0.02	0.01	0.06	0.2	0.7	5.7
Toluene	105	3.7	4.7	-	-	-1.2	0.7	1.3	2.1	4.1	8.4	24
Trichloromethane	44	0.3	0.3	0.1	4.0	0.00	0.02	0.09	0.2	0.3	0.6	1.5
1,2,4-Trimethylbenzene	92	0.4	0.5	-	-	-0.1	0.07	0.1	0.2	0.5	0.9	3.2
Vinyl acetate	2	0.01	0.00	0.01	1.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01
m,p-Xylene	104	1.6	2.3	-	-	-0.4	0.2	0.4	0.9	2.0	4.0	15
o-Xylene	96	0.5	0.8	-	-	-0.2	0.03	0.1	0.2	0.6	1.4	4.8

a) Emission rates calculated as the difference between the indoor and outdoor concentrations, multiplied by the outdoor air exchange rate. No emission rate was calculated when both the indoor and outdoor concentrations were below the MDL concentration. When only the indoor or outdoor concentration was below the MDL concentration, then the emission rate was calculated using a concentration equal to one-half the MDL concentration.

Table 46. Formaldehyde concentration and emission rates from FAU systems.

Formaldehyde Emission Rates from Forced Air Units (FAU)										
		Attic			Formaldehyde Concentrations (µg/m^3)			Formaldehyde Emission Rate[a] (µg/h)		
Home ID	Season	Temperature (°F)	Relative Humidity (%)	FAU Flowrate (m^3/h)	Supply Air	Return Air	Attic Air	FAU	Home	FAU Percent of Home
017	Summer	88.1	41.3	2,106	10.2	8.6	9.2	3,423	16,028	21
017	Winter	67.0	48.0	2,106	13.7	15.3	2.0	-3,381	6,018	-56
120	Winter	64.5	56.3	1,885	70.0	74.1	10.4	-7,681	5,093	-151
120	Winter	64.5	56.3	1,885	65.7 [b]	74.1	10.4	-15,656	5,093	-307

a) The FAU emission rate is calculated as the difference between the concentrations measured at the supply air diffuser and the return air inlet multiplied by the forced air handling unit return airflow rate. The home emission rate is calculated as the difference between the indoor air and outdoor air concentrations times the home outdoor airflow rate as determined from the PFT measurement and the home indoor air volume.
b) Second supply air concentration measurement.

Table 47. Multi-day home concentration and emission rates over three 24-hour periods for Home 033.

Home 033 Multi-Day (Summer-North)									
	Concentration ($\mu g/m^3$)				Emission Rates [d] ($\mu g/m^3$-h)			Emission Rate [e] Variation ($\mu g/m^3$-h)	
	Day 1 Indoor [a]	Day 2 Indoor [a]	Day 3 Indoor [a]	Day 1 Outdoor	Day 1	Day 2	Day 3	Absolute	Relative
Compound	ACH = 0.23	ACH = 0.29	ACH = 0.13					0.16	0.38
Acetaldehyde	75	55	109	3.2	17	15	13	3.4	0.11
Benzene	0.3	0.1	1.4	0.1[c]	0.1	0.01	0.2	0.2	1.19
2-Butoxyethanol	2.9	2.5	5.7	0.1[c]	0.7	0.7	0.7	0.1	0.05
Caprolactam	0.1[c]	0.1[c]	0.1[c]	0.1[c]	na[b]	na	na	na	na
1,4-Dichlorobenzene	0.1[c]	0.1[c]	0.1[c]	0.1[c]	na	na	na	na	na
Ethylene glycol	0.5	0.6	0.6	0.6[c]	na	na	na	na	na
Formaldehyde	58	50	64	2.3	13	14	7.8	6.1	0.29
Hexanal	13	12	21	0.2	3.1	3.4	2.7	0.8	0.12
n-Hexane	1.0	0.8	3.0	0.2[c]	0.2	0.2	0.4	0.2	0.37
d-Limonene	9.4	6.4	39	0.2[c]	2.2	1.8	4.9	3.1	0.57
1-Methyl-2-pyrrolidinone	0.2[c]	0.2[c]	0.2[c]	0.2[c]	na	na	na	na	na
Naphthalene	0.1	0.1	0.2	0.1[c]	0.01	0.01	0.01	0.01	0.21
Phenol	1.8	1.8	2.4	0.4	0.3	0.4	0.3	0.1	0.22
alpha-Pinene	16	11	26	0.1[c]	3.7	3.3	3.3	0.4	0.07
Styrene	0.9	0.2	0.8	0.1[c]	0.2	0.03	0.1	0.2	0.77
Tetrachloroethene	0.2[c]	0.2[c]	0.3	0.2[c]	na	na	0.01	0.01	1.73
Toluene	9.8	8.1	17	0.2[c]	2.3	2.3	2.1	0.2	0.04
Trichloromethane	2.2	0.7	5.4	0.2[c]	0.5	0.1	0.7	0.5	0.62
1,2,4-Trimethylbenzene	0.8	0.4	1.1	0.1[c]	0.2	0.1	0.1	0.1	0.27
Vinyl acetate	0.2[c]	0.2[c]	0.2[c]	0.2[c]	na	na	na	na	na
m,p-Xylene	4.1	2.6	5.4	0.1[c]	0.9	0.7	0.7	0.3	0.18
o-Xylene	1.0	0.3	1.2	0.1[c]	0.2	0.1	0.1	0.2	0.58

a) Day 1 is Thursday–Friday, Day 2 is Friday–Saturday, Day 3 is Saturday–Sunday
b) na: indoor and outdoor concentrations both below the concentration method detection limit thus, no emission rate was calculated; na: when fewer than two emission rates were calculated then no variations were calculated.
c) The sample was below the mass method detection limit and the concentration was calculated using one-half the method mass detection limit.
d) Emission rates calculated as the difference of the indoor concentration and Day 1 outdoor concentration multiplied by the air exchange rate.
e) Variation: *Absolute variation* is the absolute difference between the min and max emission rates; *relative variation* is the relative standard deviation of the emission rates.

Table 48. Multi-day home concentration and emission rates over three 24-hour periods for Home 041.

Home 041 Multi-Day (Winter-South)									
	Concentration (ug/m^3)				Emission Rates [d] (ug/m^3-h)			Emission Rate [e] Variation (ug/m^3-h)	
	Day 1 Indoor [a]	Day 2 Indoor [a]	Day 3 Indoor [a]	Day 1 Outdoor [a]	Day 1	Day 2	Day 3	Absolute	Relative
Compound	ACH = 0.18	ACH = 0.19	ACH = 0.20					0.01	0.04
Acetaldehyde	15	19	23	1.7	2.4	3.2	4.2	1.8	0.28
Benzene	1.2	1.3	1.2	1.0	0.04	0.1	0.04	0.01	0.13
2-Butoxyethanol	32	4.4	3.2	0.1 [c]	5.8	0.8	0.6	5.2	1.21
Caprolactam	0.1 [c]	0.1 [c]	0.1 [c]	0.1 [c]	na [b]	na	na	na [b]	na
1,4-Dichlorobenzene	0.1 [c]	0.1 [c]	0.1 [c]	0.1 [c]	na	na	na	na	na
Ethylene glycol	8.5	12	16	0.6 [c]	1.4	2.2	2.9	1.5	0.34
Formaldehyde	14	17	23	1.2	2.3	3.0	4.2	1.9	0.31
Hexanal	7.5	8.7	11	0.3	1.3	1.6	2.0	0.7	0.21
n-Hexane	0.2 [c]	1.2	0.9	1.0	na	0.04	-0.03	0.07	12.02
d-Limonene	7.7	5.8	7.3	0.4	1.3	1.0	1.4	0.3	0.14
1-Methyl-2-pyrrolidinone	0.2 [c]	0.2 [c]	0.2 [c]	0.2 [c]	na	na	na	na	na
Naphthalene	0.1 [c]	0.1 [c]	0.1 [c]	0.1 [c]	na	na	na	na	na
Phenol	2.4	1.7	2.4	1.0	0.3	0.1	0.3	0.2	0.37
alpha-Pinene	16	18	20	0.1 [c]	3.0	3.5	3.9	0.9	0.13
Styrene	2.2	1.2	1.2	0.3	0.4	0.2	0.2	0.2	0.43
Tetrachloroethene	0.2 [c]	0.2 [c]	0.2 [c]	0.2 [c]	na	na	na	na	na
Toluene	8.5	21	14	2.9	1.0	3.5	2.2	2.5	0.56
Trichloromethane	0.3	0.17 [c]	0.2	0.2 [c]	0.02	na	3E-4	0.02	1.4
1,2,4-Trimethylbenzene	1.0	0.9	1.1	0.4	0.1	0.1	0.1	0.03	0.17
Vinyl acetate	0.2 [c]	0.2 [c]	0.2 [c]	0.2 [c]	na	na	na	na	na
m,p-Xylene	3.1	2.9	3.2	1.4	0.3	0.3	0.4	0.06	0.10
o-Xylene	0.7	0.8	0.7	0.4	0.1	0.1	0.1	0.03	0.26

a) Day 1 is Thursday–Friday, Day 2 is Friday–Saturday, Day 3 is Saturday–Sunday
b) na: indoor and outdoor concentrations both below the concentration method detection limit thus, no emission rate was calculated; na: when fewer than two emission rates were calculated then no variations were calculated.
c) The sample was below the mass method detection limit and the concentration was calculated using one-half the method mass detection limit.
d) Emission rates calculated as the difference of the indoor concentration and Day 1 outdoor concentration multiplied by the air exchange rate.
e) Variation: *Absolute variation* is the absolute difference between the min and max emission rates; *relative variation* is the relative standard deviation of the emission rates.

Table 49. Multi-day home concentration and emission rates over three 24-hour periods for Home 059.

Home 059 Multi-Day (Summer-South)									
	Concentration (ug/m^3)				Emission Rates [d] (ug/m^3-h)			Emission Rate [e] Variation (ug/m^3-h)	
	Day 1 Indoor [a]	Day 2 Indoor [a]	Day 3 Indoor [a]	Day 1 Outdoor [a]	Day 1	Day 2	Day 3	Absolute	Relative
Compound	ACH = 2.25	ACH = 1.79	ACH = 1.25					1.00	0.28
Acetaldehyde	4.0	5.8	6.7	0.7	7.5	9.2	7.5	1.7	0.12
Benzene	0.1 [c]	0.1 [c]	0.3	0.1 [c]	na [b]	na	0.2	na [b]	na
2-Butoxyethanol	0.9	1.1	1.4	0.5	0.9	1.0	1.1	0.2	0.10
Caprolactam	0.1 [c]	0.1 [c]	0.1 [c]	0.1 [c]	na	na	na	na	na
1,4-Dichlorobenzene	0.1 [c]	0.1 [c]	0.1 [c]	0.1 [c]	na	na	na	na	na
Ethylene glycol	0.6 [c]	0.7 [c]	1.7 [c]	0.6 [c]	na	na	na	na	na
Formaldehyde	11	14	14	3.1	17	20	13	6.9	0.21
Hexanal	2.3	3.4	1.2	0.2	4.7	5.8	1.2	4.5	0.610
n-Hexane	0.3	1.0	1.9	0.2 [c]	0.4	1.6	2.1	1.8	0.67
d-Limonene	0.1 [c]	0.3	0.2 [c]	0.2 [c]	na	0.2	na	na	na
1-Methyl-2-pyrrolidinone	0.2 [c]	0.2 [c]	0.3 [c]	0.2 [c]	na	na	na	na	na
Naphthalene	0.1	0.3	0.4	0.1	0.1	0.3	0.4	0.3	0.53
Phenol	0.3	1.1	1.0	0.2	0.3	1.5	1.1	1.3	0.67
alpha-Pinene	0.3	0.4	0.7	0.1 [c]	0.5	0.5	0.7	0.3	0.24
Styrene	0.1	0.6	0.7	0.1 [c]	0.1	0.9	0.7	0.8	0.79
Tetrachloroethene	0.2 [c]	0.2 [c]	0.2 [c]	0.2 [c]	na	na	na	na	na
Toluene	2.9	7.0	8.9	0.2 [c]	6.1	12	10	6.1	0.33
Trichloromethane	0.2 [c]	0.2 [c]	0.2 [c]	0.2 [c]	na	na	na	na	na
1,2,4-Trimethylbenzene	0.8	2.0	2.2	0.2	1.4	3.1	2.5	1.8	0.38
Vinyl acetate	0.2 [c]	0.2 [c]	0.3 [c]	0.2 [c]	na	na	na	na	na
m,p-Xylene	2.3	5.7	6.6	0.2	4.7	10	8.1	5.1	0.35
o-Xylene	0.7	2.0	2.2	0.1 [c]	1.4	3.4	2.6	2.0	0.40

a) Day 1 is Thursday–Friday, Day 2 is Friday–Saturday, Day 3 is Saturday–Sunday
b) na: indoor and outdoor concentrations both below the concentration method detection limit thus, no emission rate was calculated; na: when fewer than two emission rates were calculated then no variations were calculated.
c) The sample was below the mass method detection limit and the concentration was calculated using one-half the method mass detection limit.
d) Emission rates calculated as the difference of the indoor concentration and Day 1 outdoor concentration multiplied by the air exchange rate.
e) Precision: *Absolute variation* is the absolute difference between the min and max emission rates; *relative variation* is the relative standard deviation of the emission rates.

Table 50. Multi-day home concentrations and emission rates for three 24-hour periods for Home 099.

Home 099 Multi-Day (Winter-North)									
	Concentration (ug/m^3)				Emission Rates [d] (ug/m^3-h)			Emission Rate [e] Variation (ug/m^3-h)	
	Day 1 Indoor [a]	Day 2 Indoor [a]	Day 3 Indoor [a]	Day 1 Outdoor [a]	Day 1	Day 2	Day 3	Absolute	Relative
Compound	ACH = na [b]	ACH = 0.17	ACH = 0.16					0.01	0.05
Acetaldehyde	57	86	57	1.8	na [b]	14.7	9.0	5.7	0.34
Benzene	2.4	3.0	2.8	0.8	na	0.4	0.3	0.07	0.13
2-Butoxyethanol	6.3	4.7	4.8	0.1 [c]	na	0.8	0.8	0.04	0.04
Caprolactam	0.1 [c]	0.1 [c]	0.1 [c]	0.1 [c]	na	na	na	na [b]	na
1,4-Dichlorobenzene	0.3	0.1	0.1	0.1 [c]	na	0.0	0.0	0.0	0.0
Ethylene glycol	14	11	13	0.6 [c]	na	1.8	2.0	0.2	0.09
Formaldehyde	86	94	86	3.1	na	15.9	13.6	2.4	0.11
Hexanal	30	28	29	0.05 [c]	na	4.8	4.7	0.2	0.02
n-Hexane	3.0	4.4	4.5	0.2	na	0.7	0.7	0.03	0.03
d-Limonene	24	29	29	0.1 [c]	na	5.0	4.7	0.4	0.06
1-Methyl-2-pyrrolidinone	0.2 [c]	0.2 [c]	0.2 [c]	0.2 [c]	na	na	na	na	na
Naphthalene	0.6	0.6	0.6	0.1 [c]	na	0.1	0.1	0.004	0.03
Phenol	2.2	2.5	2.4	0.4	na	0.4	0.3	0.04	0.09
alpha-Pinene	15	15	15	0.1 [c]	na	2.6	2.4	0.3	0.08
Styrene	0.8	1.1	1.1	0.1 [c]	na	0.2	0.2	0.02	0.07
Tetrachloroethene	0.2	0.2	0.2 [c]	0.2 [c]	na	0.008	na	na	na
Toluene	16	21	19	1.1	na	3.4	2.9	0.5	0.11
Trichloromethane	4.3	4.5	3.6	0.2 [c]	na	0.8	0.6	0.2	0.21
1,2,4-Trimethylbenzene	4.2	4.3	5.6	0.2	na	0.7	0.9	0.2	0.15
Vinyl acetate	0.2 [c]	0.2 [c]	0.2 [c]	0.2 [c]	na	na	na	na	na
m,p-Xylene	9.0	10	12	0.7	na	1.7	1.9	0.2	0.08
o-Xylene	3.5	3.9	5.0	0.2	na	0.7	0.8	0.1	0.12

a) Day 1 is Thursday–Friday, Day 2 is Friday–Saturday, Day 3 is Saturday–Sunday
b) na: indoor and outdoor concentrations both below the concentration method detection limit thus, no emission rate was calculated; na: when fewer than two emission rates were calculated then no variations were calculated.
c) The sample was below the mass method detection limit and the concentration was calculated using one-half the method mass detection limit.
d) Emission rates calculated as the difference of the indoor concentration and Day 1 outdoor concentration multiplied by the air exchange rate.
e) Precision: *Absolute variation* is the absolute difference between the min and max emission rates, *relative precision* is the relative standard deviation of the emission rate.

Table 51. Multi-season home concentration and emission rates over 24-hour periods in three seasons for Home 005.

Home 005 Multi-season									
	Concentration (ug/m^3)				Emission Rates [d] (ug/m^3-h)			Emission Rate Variation [e] (ug/m^3-h)	
	Day 1 Indoor [a]	Day 2 Indoor [a]	Day 3 Indoor [a]	Outdoor [a]	Day 1	Day 2	Day 3	Absolute	Relative
Compound	ACH = 0.16	ACH = 0.15	ACH = 0.27					0.12	0.34
Acetaldehyde	64	49	21	3.3/ 4.5 / 0.2	9.7	6.6	5.6	4.2	0.30
Benzene	3.1	7.4	4.9	0.1[c] / 0.1[c] / 0.6	0.5	1.1	1.2	0.7	0.41
2-Butoxyethanol	5.7	11	1.5	0.1[c] / 0.1[c] / 0.1[c]	0.9	1.6	0.4	1.2	0.63
Caprolactam	0.1[c]	0.1[c]	0.1[c]	0.1[c] / 0.1[c] / 0.1[c]	na [b]	na	na	na [b]	na
1,4-Dichlorobenzene	451	13	1.8	0.8 / 0.1[c] / 0.1[c]	72	1.9	0.5	72	1.65
Ethylene glycol	20	7.2	0.5[c]	0.6[c] / 0.6[c] / 0.6[c]	3.2	1.0	na	3.2	1.17
Formaldehyde	111	72	44	6.6 / 3.0 / 2.3	17	10	11	6.5	0.27
Hexanal	37	27	15	0.0[c] / 0.0[c] / 0.7	5.9	4.0	4.0	1.9	0.24
n-Hexane	4.5	15	11	0.1[c] / 0.5 / 0.2[c]	0.7	2.1	2.8	2.1	0.58
d-Limonene	9.9	12	21	0.1[c] / 0.1[c] / 0.9	1.6	1.8	5.3	3.8	0.73
1-Methyl-2-pyrrolidinone	0.2[c]	0.2[c]	0.2[c]	0.2[c] / 0.2[c] / 0.2[c]	na	na	na	na	na
Naphthalene	0.5	0.8	0.4	0.1[c] / 0.2 / 0.1[c]	0.1	0.1	0.1	0.02	0.11
Phenol	6.4	4.4	2.9	0.8 / 0.5 / 0.9	0.9	0.6	0.5	0.4	0.29
alpha-Pinene	43	38	13	0.1[c] / 0.1[c] / 0.1[c]	6.8	5.6	3.6	3.2	0.30
Styrene	3.7	3.4	1.3	0.1[c] / 0.5 / 0.3	0.6	0.4	0.3	0.3	0.36
Tetrachloroethene	0.2[c]	0.2[c]	0.2[c]	0.2[c] / 0.2[c] / 0.2[c]	na	na	na	na	na
Toluene	31	64	25	1.3 / 3.2 / 1.8	4.7	9.2	6.0	4.5	0.35
Trichloromethane	0.2[c]	0.2[c]	0.2[c]	0.2[c] / 0.2[c] / 0.2[c]	na	na	na	na	na
1,2,4-Trimethylbenzene	5.3	10	3.7	0.1[c] / 0.8 / 0.4	0.8	1.4	0.9	0.6	0.30
Vinyl acetate	0.2[c]	0.2[c]	0.2[c]	0.2[c] / 0.2[c] / 0.2[c]	na	na	na	na	na
m,p-Xylene	17	38	14	0.8 / 2.3 / 1.1	2.6	5.4	3.5	2.8	0.37
o-Xylene	6.4	12	4.5	0.1[c] / 0.7 / 0.3	1.0	1.7	1.1	0.7	0.28

a) Day 1 is Summer North, Day 2 is Fall North, Day 3 is Winter North field session
b) na: indoor and outdoor concentrations both below the concentration method detection limit thus, no emission rate was calculated; na: when fewer than two emission rates were calculated then no variations were calculated.
c) The sample was below the mass method detection limit and the concentration was calculated using one-half the method mass detection limit.
d) Emission rate is calculated as the difference of the indoor concentration and the outdoor concentration multiplied by the air exchange rate.
e) Variation: *Absolute variation* is the absolute difference between the min and max emission rates, *relative variation* is the relative standard deviation of the emission rates.

Table 52. Multi-season home concentration and emission rates over 24-hour periods in three seasons for Home 006.

Home 006 Multi-season									
	Concentration (ug/m^3)				Emission Rates [d] (ug/m^3-h)			Emission Rate [e] Variation (ug/m^3-h)	
	Day 1 Indoor [a]	Day 2 Indoor [a]	Day 3 Indoor [a]	Outdoor [a]	Day 1	Day 2	Day 3	Absolute	Relative
Compound	ACH = 0.16	ACH = 0.63	ACH = 0.23					0.47	0.75
Acetaldehyde	43	14	22	3.3 / 4.5 / 0.2	6.4	6.1	5.0	1.4	0.13
Benzene	1.0	0.3	1.3	0.1[c] / 0.1[c] / 0.6	0.1	0.1	0.2	0.04	0.15
2-Butoxyethanol	3.7	1.2	7.2	0.1[c] / 0.1[c] / 0.1[c]	0.6	0.7	1.6	1.1	0.59
Caprolactam	0.1[c]	0.1[c]	0.1[c]	0.1[c] / 0.1[c] / 0.1[c]	na [b]	na	na	na [b]	na
1,4-Dichlorobenzene	0.1[c]	0.1[c]	0.1[c]	0.8 / 0.1[c] / 0.1[c]	-0.1	na	na	na	na
Ethylene glycol	7.0	0.5[c]	0.6[c]	0.6[c] / 0.6[c] / 0.6[c]	1.0	na	na	na	na
Formaldehyde	61	23	33	6.6 / 3.0 / 2.3	8.8	12.5	7.0	5.5	0.30
Hexanal	28	2.8	15	0.0[c] / 0.0[c] / 0.7	4.4	1.7	3.3	2.7	0.43
n-Hexane	1.8	1.2	1.3	0.1[c] / 0.5 / 0.2[c]	0.3	0.5	0.3	0.2	0.35
d-Limonene	9.9	1.6	19	0.1[c] / 0.1[c] / 0.9	1.6	0.9	4.1	3.2	0.77
1-Methyl-2-pyrrolidinone	0.2[c]	0.2[c]	0.2[c]	0.2[c] / 0.2[c] / 0.2[c]	na	na	na	na	na
Naphthalene	0.1	0.3	0.1	0.1[c] / 0.2 / 0.1[c]	0.01	0.04	0.01	0.03	0.78
Phenol	3.7	1.5	1.9	0.8 / 0.5 / 0.9	0.5	0.6	0.2	0.4	0.45
alpha-Pinene	32	10	11	0.1[c] / 0.1[c] / 0.1[c]	5.1	6.4	2.5	3.9	0.42
Styrene	1.9	1.6	1.1	0.1[c] / 0.5 / 0.3	0.3	0.7	0.2	0.5	0.70
Tetrachloroethene	0.2[c]	0.2[c]	0.2[c]	0.2[c] / 0.2[c] / 0.2[c]	na	na	na	na	na
Toluene	13	11	11	1.3 / 3.2 / 1.8	1.8	4.7	2.1	2.9	0.56
Trichloromethane	0.2[c]	0.2[c]	0.2[c]	0.2[c] / 0.2[c] / 0.2[c]	na	na	na	na	na
1,2,4-Trimethylbenzene	1.1	1.6	1.6	0.1[c] / 0.8 / 0.4	0.2	0.5	0.3	0.3	0.53
Vinyl acetate	0.2[c]	0.2[c]	0.2[c]	0.2[c] / 0.2[c] / 0.2[c]	na	na	na	na	na
m,p-Xylene	5.1	5.2	4.6	0.8 / 2.3 / 1.1	0.7	1.8	0.8	1.1	0.56
o-Xylene	1.3	1.6	1.1	0.1[c] / 0.7 / 0.2	0.2	0.6	0.2	0.4	0.67

a) Day 1 is Summer North, Day 2 is Fall North, Day 3 is Winter North field session
b) na: indoor and outdoor concentrations both below the concentration method detection limit thus, no emission rate was calculated; na: when fewer than two emission rates were calculated then no variations were calculated.
c) The sample was below the mass method detection limit and the concentration was calculated using one-half the method mass detection limit.
d) Emission rate is calculated as the difference of the indoor concentration and the outdoor concentration multiplied by the air exchange rate.
e) Variation: *Absolute variation* is the absolute difference between the min and max emission rates, *relative variation* is the relative standard deviation of the emission rates.

Table 53. Multi-season home concentration and emission rates over 24-hour periods in three seasons for Home 013.

Home 013 Multi-season								
	Concentration (ug/m^3)				Emission Rates [d] (ug/m^3-h)		Emission Rate [e] Variation (ug/m^3-h)	
	Day 1 Indoor [a]	Day 2 Indoor [a]	Day 1 Outdoor [a]	Day 2 Outdoor [a]	Day 1	Day 2	Absolute	Relative
Compound	ACH = 0.16	ACH = 0.81					0.65	0.95
Acetaldehyde	73	15	1.4	3.1	11	9.9	1.5	0.10
Benzene	2.2	2.1	0.1[c]	0.2	0.3	1.5	1.2	0.92
2-Butoxyethanol	5.2	1.5	0.1[c]	0.1[c]	0.8	1.2	0.4	0.27
Caprolactam	0.1[c]	0.1[c]	0.1[c]	0.1[c]	na [b]	na	na	na
1,4-Dichlorobenzene	0.4	0.4	0.1[c]	0.2	0.04	0.1	0.1	0.80
Ethylene glycol	30	7.8	0.6[c]	0.6[c]	4.7	5.8	1.2	0.16
Formaldehyde	100	45	0.7	0.2	16	35	21	0.55
Hexanal	22	1.0	0.0[c]	0.0[c]	3.5	0.7	2.8	0.92
n-Hexane	4.3	4.2	0.1[c]	0.7	0.7	2.8	2.1	0.87
d-Limonene	19	2.6	0.1[c]	0.1[c]	3.1	2.0	1.0	0.29
1-Methyl-2-pyrrolidinone	0.6	0.2[c]	0.2[c]	0.2[c]	0.1	na	0.08	na
Naphthalene	0.4	0.4	0.1[c]	0.2	0.1	0.1	0.08	0.60
Phenol	3.5	1.1	0.7	0.4	0.4	0.6	0.1	0.17
alpha-Pinene	58	17	0.1[c]	0.1[c]	9.3	13	4.1	0.25
Styrene	2.8	1.0	0.1[c]	0.1[c]	0.4	0.7	0.3	0.35
Tetrachloroethene	0.2[c]	0.2[c]	0.2[c]	0.2[c]	na	na	na	na
Toluene	114	66	0.6	5.0	18	50	31	0.65
Trichloromethane	1.3	0.4	0.2[c]	0.2[c]	0.2	0.2	0.01	0.02
1,2,4-Trimethylbenzene	2.5	3.3	0.1[c]	1.1	0.4	1.7	1.4	0.91
Vinyl acetate	0.2[c]	0.2[c]	0.2[c]	0.2[c]	na	na	na	na
m,p-Xylene	21	16	0.1[c]	3.2	3.2	11	7.4	0.75
o-Xylene	5.8	5.1	0.1[c]	1.0	0.9	3.3	2.4	0.80

a) Day 1 is Summer North, Day 2 is Fall North
b) na: indoor and outdoor concentrations both below the concentration method detection limit thus, no emission rate was calculated; na: when fewer than two emission rates were calculated then no variations were calculated.
c) The sample was below the mass method detection limit and the concentration was calculated using one-half the method mass detection limit.
d) Emission rate is calculated as the difference of the indoor concentration and the outdoor concentration multiplied by the air exchange rate.
e) Variation: *Absolute variation* is the absolute difference between the min and max emission rates, *relative variation* is the relative standard deviation of the emission rates.

Table 54. Multi-season home concentration and emission rates over 24-hour periods in three seasons for Home 019.

Home 019 Multi-season									
	Concentration (ug/m^3)				Emission Rates (ug/m^3-h) [d]			Emission Rate Variation [e]	
	Day 1 Indoor [a]	Day 2 Indoor [a]	Day 3 Indoor [a]	Outdoor [a]	Day 1	Day 2	Day 3	Absolute	Relative
Compound	ACH = na	ACH = 0.29	ACH = 0.11					0.18	0.64
Acetaldehyde	2.7	15	22	3.1 / 3.1 / 0.7	na [b]	3.5	2.4	1.1	0.27
Benzene	0.1[c]	0.9	1.7	0.1[c] / 0.2 / 0.7	na	0.2	0.1	0.09	0.39
2-Butoxyethanol	0.1[c]	3.6	9.9	0.1[c] / 0.1[c] / 0.1[c]	na	1.0	1.1	0.04	0.03
Caprolactam	0.1[c]	0.1[c]	0.1[c]	0.1[c] / 0.1[c] / 0.1[c]	na	na	na	na [b]	na
1,4-Dichlorobenzene	0.1[c]	0.1[c]	0.1	0.1[c] / 0.2 / 0.1[c]	na	-0.03	0.005	0.03	-2.0
Ethylene glycol	0.7[c]	0.5[c]	0.6[c]	0.6[c] / 0.6[c] / 0.6[c]	na	na	na	na	na
Formaldehyde	4.7	24	36	2.2 / 2.0 / 2.9	na	6.4	3.6	2.8	0.40
Hexanal	0.1[c]	1.1	14	0.1[c] / 0.0[c] / 0.1[c]	na	0.3	1.6	1.3	0.94
n-Hexane	0.2[c]	2.0	1.9	0.2[c] / 0.7 / 0.2[c]	na	0.4	0.2	0.18	0.45
d-Limonene	0.2[c]	3.9	12.7	0.2[c] / 0.1[c] / 0.2[c]	na	1.1	1.4	0.31	0.18
1-Methyl-2-pyrrolidinone	0.7	0.2[c]	0.2[c]	0.2[c] / 0.2[c] / 0.2[c]	na	na	na	na	na
Naphthalene	0.1[c]	0.3	0.2	0.1[c] / 0.2 / 0.1[c]	na	0.02	0.02	0	0.07
Phenol	0.9	0.9	2.1	0.5 / 0.4 / 0.4	na	0.1	0.2	0.06	0.25
alpha-Pinene	0.5	8.8	12	0.1[c] / 0.1[c] / 0.1[c]	na	2.5	1.3	1.2	0.44
Styrene	0.1[c]	0.3	1.4	0.1[c] / 0.1[c] / 0.1[c]	na	0.1	0.1	0.08	0.54
Tetrachloroethene	0.2[c]	0.2[c]	0.7	0.2[c] / 0.2[c] / 0.2[c]	na	na	0.1	na	na
Toluene	1.0	13	12	1.1 / 5.0 / 1.0	na	2.3	1.2	1.1	0.46
Trichloromethane	0.2[c]	0.2[c]	0.4	0.2[c] / 0.2[c] / 0.2[c]	na	na	0.03	na	na
1,2,4-Trimethylbenzene	0.1[c]	1.8	2.1	0.1[c] / 1.1 / 0.1	na	0.2	0.2	0.02	0.05
Vinyl acetate	0.2[c]	0.2[c]	0.2[c]	0.2[c] / 0.2[c] / 0.2[c]	na	na	na	na	na
m,p-Xylene	0.6[c]	6.0	6.4	1.5 / 3.2 / 0.6	na	0.8	0.7	0.17	0.16
o-Xylene	0.1[c]	1.9	2.3	0.1[c] / 1.0 / 0.1	na	0.2	0.2	0.01	0.03

a) Day 1 is Summer North, Day 2 is Fall North, Day 3 is Winter North field session
b) na: indoor and outdoor concentrations both below the concentration method detection limit thus, no emission rate was calculated or Day 1 with no PFT measurement; na: when fewer than two emission rates were calculated then no variations were calculated.
c) The sample was below the mass method detection limit and the concentration was calculated using one-half the method mass detection limit.
d) Emission rate is calculated as the difference of the indoor concentration and the outdoor concentration multiplied by the air exchange rate.
e) Variation: *Absolute* is the absolute difference between the min and max emission rates, *relative* is the relative standard deviation of the emission rates.

Table 55. Normality test results for formaldehyde and acetaldehyde concentration, air exchange rate, indoor and outdoor temperature and relative humidity, composite wood loading, home age, and window usage.

Normalized Variable	N	Kolmogorov-Smirnov D	p
Log of the formaldehyde concentration ($\mu g/m^3$)	105	0.062	>0.15
Log of the acetaldehyde concentration ($\mu g/m^3$)	105	0.074	>0.15
Inverse of the air exchange rate (hours)	106	0.085	0.06
Indoor temperature (°F)	103	0.080	0.10
Indoor relative humidity squared (%)	103	0.062	>0.15
Outdoor temperature (°F)	39	0.125	0.12
Outdoor relative humidity (%)	39	0.144	0.06
Log of composite wood loading (ft^2/1,000 ft^3) [a]	107	0.082	0.08
Home age (years)	105	0.060	>0.15
Square root of non-zero window usage (ft^2-hrs)	74	0.094	0.10

Normality Test Results

a) Log of composite wood loading (i.e., ft^2 of composite wood per 1,000 ft^3 of indoor air volume).

Table 56. Group comparisons for formaldehyde and acetaldehyde concentrations.

Formaldehyde and Acetaldehyde Concentrations Group Comparisons [a]

North vs. South Non-Mechanical Homes

Formaldehyde	N	Mean	Standard Error	t	Degrees of Freedom	Probability of [b] no Difference
North	25	3.88	0.11	3.412	50	**0.001**
South	47	3.40	0.08			
Acetaldehyde						
North	25	3.36	0.16	0.996	43	0.32
South	47	2.78	0.10			

Summer vs. Winter Seasonal Repeat Homes

Formaldehyde	N	Mean	Standard Error	t	Degrees of Freedom	Probability of no Difference
Summer	19	3.42	0.23	0.001	36	0.50
Winter	19	3.42	0.11			
Acetaldehyde						
Summer	19	2.68	0.27	0.996	36	0.16
Winter	19	2.98	0.14			

Mechanical vs. Non-Mechanical

Formaldehyde	N	Mean	Standard Error	t	Degrees of Freedom	Probability of no Difference
DOA	13	4.17	0.11	4.710	25	**0.0001**
Non-Mechanical	72	3.57	0.07			
HRV	5	3.08	0.37	1.287	4	0.27
Non-Mechanical	72	3.57	0.07			
Acetaldehyde						
DOA	13	3.63	0.18	3.167	18	**0.005**
Non-Mechanical	72	2.98	0.09			
HRV	5	2.09	0.34	2.524	4	0.07
Non-Mechanical	72	2.98	0.09			

DOA vs. HRV

Formaldehyde	N	Mean	Standard Error	t	Degrees of Freedom	Probability of no Difference
DOA	13	4.17	0.11	2.811	4	**0.05**
HRV	5	3.08	0.37			
Acetaldehyde						
DOA	13	3.63	0.18	3.979	4	**0.02**
HRV	5	2.09	0.34			

a) The log of formaldehyde and acetaldehyde concentrations (µg/m^3) were used to normalize the data.
b) Probability that there is a difference between the two population means, p≤ 0.05, are **bolded**.

Table 57. Group comparison for outdoor air exchange rates and window usage.

Outdoor Exchange Rate and Window Usage Group Comparisons						
North vs. South; Non-Mechanical Homes						
ACH [a]	N	Mean	Standard Error	t	Degrees of Freedom	Probability of [d] no Difference
North	25	4.52	0.48	0.649	44	0.52
South	48	4.15	0.31			
Window Usage [b,c]						
North	16	12.7	2.50	0.322	26	0.75
South	38	13.7	1.53			
Summer vs. Winter; Seasonal Repeat Homes						
ACH [a]	N	Mean	Standard Error	t	Degrees of Freedom	Probability of no Difference
Summer	19	3.53	0.65	1.433	36	0.08
Winter	19	4.77	0.57			
Window Usage [b,c]						
Summer	7	17.2	4.21	2.341	12	**0.02**
Winter	7	6.1	2.19			
Mechanical vs. Non-Mechanical						
ACH [a]	N	Mean	Standard Error	t	Degrees of Freedom	Probability of no Difference
DOA	13	5.07	0.80	0.931	14	0.37
Non-Mechanical	73	4.28	0.26			
HRV	5	1.41	0.48	5.248	6	**0.002**
Non-Mechanical	73	4.28	0.26			
Window Usage [b,c]						
DOA	10	14.6	3.40	0.340	11	0.74
Non-Mechanical	54	13.4	1.30			
HRV	3	24.24	4.81	2.181	2	0.16
Non-Mechanical	54	13.4	1.30			
DOA vs. HRV						
ACH [a]	N	Mean	Standard Error	t	Degrees of Freedom	Probability of no Difference
DOA	13	5.07	0.80	3.906	6	**0.008**
HRV	5	1.41	0.48			
Window Usage [b,c]						
DOA	10	14.6	3.40	1.636	2	0.24
HRV	3	24.2	4.81			

a) The inverse of air changes per hour (ach), residence time (hrs), was used to normalize the data.
b) The square root of window usage (ft^2-hrs) was utilized to normalize the data.
c) Window usage was measured during the 24-hour air sampling period.
d) Probability that there is a difference between the two population means, p≤ 0.05, are **bolded.**

Table 58. Correlations of indoor formaldehyde concentrations with home characteristics and with indoor and outdoor environmental conditions.

Indoor Formaldehyde Concentration Correlations						
	Pearson Correlation [a]			Spearman Correlation		
	N	Correlation Coefficient	Probability of [d] No Correlation	N	Correlation Coefficient	Probability of [d] No Correlation
Home Characteristics						
Home age (years)	102	-0.155	0.121	102	-0.148	0.137
Composite wood loading [c] (ft^2/1,000 ft^3)	104	-0.068	0.495	104	-0.052	0.600
New cabinetry [b] (Y/N within 6 months)	102	-0.105	0.292	102	-0.120	0.230
New Furniture [b] (Y/N within 6 months)	103	0.132	0.185	103	0.090	0.365
Air fresheners present [b] (Y/N during Test Day)	88	-0.063	0.559	88	-0.031	0.775
Outdoor air exchange rate [c] (Outdoor air residence time - h)	103	0.496	**< 0.0001**	103	-0.494	**< 0.0001**
Environmental Conditions						
Indoor temperature (℉)	100	0.236	**0.018**	100	0.228	**0.022**
Indoor relative humidity [c] (%)	100	0.027	0.791	100	0.125	0.215
Outdoor temperature (℉)	92	0.051	0.628	92	0.091	0.386
Outdoor relative humidity (%)	92	0.164	0.119	92	0.163	0.120

a) Pearson correlations use the normalized log of the indoor formaldehyde concentrations.
b) Present or absent responses.
c) Pearson correlations use the normalized variables: log of composite wood loading (i.e., ft^2 of composite wood per 1,000 ft^3 of indoor air volume), inverse of the outdoor air exchange rate (i.e., outdoor air residence time), and indoor relative humidity squared.
d) Probability that there is no correlation, p≤ 0.05, are **bolded.**

Table 59. Correlation of indoor acetaldehyde concentrations with home characteristics and with indoor and outdoor environmental conditions.

Indoor Acetaldehyde Concentration Correlations						
	Pearson Correlation [a]			Spearman Correlation		
	N	Correlation Coefficient	Probability of [d] No Correlation	N	Correlation Coefficient	Probability of [d] No Correlation
Home Characteristics						
Home age (years)	102	-0.091	0.363	102	-0.063	0.527
Composite wood loading [c] (ft^2/1,000 ft^3)	104	-0.301	**0.002**	104	-0.289	**0.003**
New cabinetry [b] (Y/N within 6 months)	102	-0.009	0.925	102	-0.019	0.853
New Furniture [b] (Y/N within 6 months)	103	0.094	0.343	103	0.089	0.374
Air fresheners present [b] (Y/N during Test Day)	88	-0.089	0.366	88	-0.084	0.394
Outdoor air exchange rate [c] (Outdoor air residence time - h)	103	0.651	**< 0.0001**	103	-0.710	**< 0.0001**
Environmental Conditions						
Indoor temperature (℉)	100	-0.093	0.355	100	-0.091	0.367
Indoor relative humidity [c] (%)	100	-0.109	0.281	100	0.071	0.484
Outdoor temperature (℉)	92	-0.179	0.089	92	-0.139	0.188
Outdoor relative humidity (%)	92	-0.006	0.954	92	0.022	0.832

a) Pearson correlations use the normalized log of the indoor formaldehyde concentrations.
b) Present or absent responses.
c) Pearson correlations use the normalized variables: log of composite wood loading (i.e., ft^2 of composite wood per 1,000 ft^3 of indoor air volume), inverse of the outdoor air exchange rate (i.e., outdoor air residence time), and indoor relative humidity squared.
d) Probability that there is no correlation, $p < 0.05$, are **bolded.**

Table 60. Homeowner reported mechanical ventilation system operation and choices-1.

Mechanical Ventilation System Operation and Choices		
Variable	N [a]	%
Was the operation of the system explained to you when you bought or moved into the house? – Answered Yes	24	78
Do you feel you understand how the system works? – Answered Yes	24	63
Do you feel you understand how to operate it properly? – Answered Yes	24	83
How is the system typically used in each season?		
- Summer Continuous	22	32
- Summer Frequent	22	45
- Summer Infrequent	22	14
- Summer Never	22	9.1
- Fall Continuous	21	36
- Fall Frequent	21	9.1
- Fall Infrequent	21	36
- Fall Never	21	14
- Winter Continuous	22	18
- Winter Frequent	22	23
- Winter Infrequent	22	32
- Winter Never	22	27
- Spring Continuous	22	27
- Spring Frequent	22	27
- Spring Infrequent	22	36
- Spring Never	22	14
Why did you choose the system?		
- Came with the house	22	91
- A household member has health condition	22	0
- Wanted filtered fresh outdoor air	22	5
- Affordable cost	22	0
- Good reliability	22	5
- Reduced energy costs	22	5
- Other:	22	5

a) Number of homes with either a DOA or HRV mechanical outdoor air system and with completed responses to questions. Does not include nighttime cooling systems (e.g., WHF, RAD), evaporative cooling systems, or window fans. Total of 26 homes with mechanical outdoor air systems (i.e., 17 DOA systems and 9 HRV systems).

Table 61. Homeowner reported mechanical ventilation system operation and choices-2.

Mechanical Ventilation System Operation and Choices		
Variable	N [a]	%
What do you like about the system?		
- Fresh air	21	52
- Quiet	21	48
- Reduced odors	21	14
- Reduced energy costs	21	19
- Reduced allergies	21	10
- Reduced concern about indoor air quality	21	24
- Other	21	14
- None of the above	21	10
What don't you like about the system?		
- Too noisy	19	26
- Too drafty	19	26
- Increases odors	19	0
- Hard to operate	19	0
- Hard to maintain	19	11
- Too expensive	19	11
- Too quiet	19	0
- Not Effective	19	32
- Other	19	26
- None of the above	19	21
Please list any additional problems or provide any additional comments you have		
- None	14	64
- Do have problems or comments	14	36

a) Number of homes with either a DOA or HRV mechanical outdoor air system and with completed responses to questions. Does not include nighttime cooling systems (e.g., WHF, RAD), evaporative cooling systems, or window fans. Total of 26 homes with mechanical outdoor air systems (i.e., 17 DOA systems and 9 HRV systems).

Table 62. Homeowner reported IAQ related improvement choices.

Home IAQ Related Improvement Choices		
Variable	N [a]	%
What special measures or choices have you or the builder taken to improve the quality of the air in your home?		
None	105	24
Upgrade my central air filter	105	25
High efficiency vacuum cleaner with special features such as filters to trap more particles	105	27
Whole house vacuum	105	6.7
Low-emission carpets, furniture, paint, or cabinets	105	2.9
Hard flooring instead of carpeting	105	33
Carbon monoxide alarm	105	28
Special kitchen range hood	105	7.6
Extra exhaust fans	105	2.9
Whole house ventilation system	105	14
Other (Specify):	105	11

a) Number of homes with completed data.

4.0 Conclusions and Recommendations

4.1 Summary

In setting previous building energy design standards, the Energy Commission had assumed a certain level of outdoor air ventilation from occupant use of windows and mechanical devices. However, because homes built within the last few years were designed to be relatively airtight in order to provide comfort and avoid wasting energy, concerns were raised that the occupant use of windows, doors, and mechanical ventilation devices may not provide adequate ventilation with outdoor air, and may contribute to unacceptable indoor air quality. Information on household ventilation practices of occupants was needed by the Energy Commission. A 2005 mail survey on occupants' use of windows and mechanical ventilation equipment in 1,515 new homes in California indicated that many homeowners never use their windows for ventilation. From this mail survey, a concern emerged that the current California residential building codes, where simply providing openable windows is currently a design option, may result in homes that do not receive adequate ventilation to control indoor air contaminants to acceptable levels.

For this reason a large field study was initiated to measure window and mechanical ventilation system usage, outdoor air ventilation rates, sources and concentrations of indoor air contaminants, and occupant perceptions.

This project had the following six specific study objectives:

1. Determine how residents use windows, doors, and mechanical ventilation devices such as exhaust fans and central heating and air-conditioning systems.

2. Measure and characterize indoor air quality (IAQ), ventilation, and the potential sources of indoor pollutants.

3. Determine occupant perceptions of, and satisfaction with, the IAQ in their homes.

4. Examine the relationships among home ventilation characteristics, measured and perceived IAQ, and house and household characteristics.

5. Identify the incentives and barriers that influence people's use of windows, doors, and mechanical ventilation devices for adequate air exchange.

6. Identify the incentives and barriers related to people's purchases and practices that improve IAQ, such as the use of low-emitting building materials and improved air filters.

This study provides, for the first time, statewide, accurate and current information on both ventilation and IAQ in new California homes. Indoor air quality and household ventilation practices were obtained from multiple seasons and regions of the state, which will help characterize the full range of indoor air contaminant exposure in such homes. Measured levels of ventilation and IAQ were compared to current guidelines and standards. Information on the use of windows, fans, and central systems collected in this field study will help establish realistic values for developing state standards for building energy efficiency.

The Energy Commission may use the study results as a scientific basis to revise the state's building energy efficiency standards in order to provide more healthful, energy-efficient homes in California. The study results will improve ARB's ability to identify current sources of indoor air contaminants, to assess Californians current exposure to measured toxic air contaminants, and to recommend effective strategies for reducing indoor air pollution.

4.2 Conclusions

Objective 1. Determine how residents use windows, doors, and mechanical ventilation devices, such as exhaust fans and central heating and air-conditioning systems.

This study's field measurements consisted of measurements during both the 24-hour Test Day and the preceding week. Generally, the results of measurements during the 24-hour Test Day reflected the average observed during the preceding week.

<u>Occupant Use of Windows and Doors for Ventilation</u>. According to the UCB mail survey preceding this field study, many homeowners never open their windows or doors for ventilation as a result of their concerns for security/safety, noise, dust, and odor concerns. In this field study, 32% of the homes did not use their windows during the 24-hour Test Day, and 15% of the homes did not use their windows during the entire preceding week. Most of the homes with no window usage were homes in the winter field session. Thus, a substantial percentage of homeowners never open their windows, especially in the winter season.

<u>Occupant Use of Mechanical Exhaust Air Systems</u>. A total of 78% of the homes during the 24-hour Test Day, and 15% during the entire preceding week, never used the kitchen exhaust fan. A total of 47% never used the bathroom fans during the 24-hour Test Day and 27% never used the fans during the entire preceding week. Thus, very few homeowners utilize their kitchen and bathroom exhaust fans.

<u>Occupant Use of Mechanical Outdoor Air Systems</u>**.** For the two types of mechanical outdoor air systems encountered in the field study—ducted outdoor air (DOA) systems and heat recovery ventilator systems (HRV)—the median Test Day usage was 2.5 hours for

the DOA systems (n=14) and 24 hours for HRV systems (n=8). These data indicate that the DOA systems, which typically are operated intermittently and in conjunction with the operation of the FAU fan, operate for only a small portion of the day, while the HRV systems are typically operated continuously. To ensure adequate delivery of outdoor air to the home, DOA systems should have a fan cycler, so that even if the thermostat fan switch does not operate the FAU fan, the fan is operated for a minimum percentage of time. Few of the homes in this study with operational DOA systems had fan cyclers; just 4 of the 14 homes. Three of these four homes met the 2008 Building Energy Efficiency Standards operational time requirements for intermittently operated residential outdoor air mechanical ventilation systems. The 10 operational DOA systems, which do not have fan cyclers and were operated by the thermostat fan switch in the "auto" mode, do not meet the 2008 Building Energy Efficiency Standards operational time requirements.

It is important to note that while the thermostat fan switch could be set to the "on" position, and thus overcome the low operational times of some of these DOA systems, this would not be a very energy-efficient means of providing outdoor air to the home. The FAU fan system is a large fan designed to provide the large supply airflow rates required for heating or cooling the air in the home and operating the FAU fan continuously would be a large and costly consumption of electricity. The flow rates of outdoor air required for ventilating homes is just a fraction (e.g., 5%–10%) of the total supply airflow rate delivered by the FAU fan. Thus, to ensure adequate and energy efficient delivery of outdoor air to the home, DOA systems should include a fan cycler with fan cycle times and outdoor airflow rates set to provide sufficient outdoor air ventilation.

Occupant Use of Mechanical Nighttime Cooling Systems**.** For the two types of nighttime cooling systems encountered in the field study—whole house fan (WHF) systems and FAU Return Air Damper (RAD) systems—the median Test Day usage was 0.7 hours for WHF systems and 5.3 hours for RAD systems. Use of these systems is confined primarily to the summer months. Thus, the nighttime cooling systems were operated for relatively few hours each day, with the RAD systems having longer operating times.

Occupant Use of Forced Air Unit (FAU) Systems. The median Test Day usage for FAUs was 1.1 hours. A total of 32% of the homes had zero usage of the FAU during the 24-hour Test Day, and 11% had zero usage during the entire preceding week. Thus, the FAU systems were operated for relatively few hours each day. As discussed above, this low operational time of the FAU fan limits the capability of DOA systems, which depend upon the operation of the FAU fan to deliver the required outdoor air.

Objective 2. Measure and characterize indoor air quality, ventilation, and the potential sources of indoor pollutants.

Forced Air Heating/Cooling System Duct Leakage. A total of 86% of the homes had duct leakage exceeding the California Title 24 maximum of 6%. Thus, new homes in California have relatively leaky ducts.

Home Building Envelope Air Leakage Area. The median ACH_{50} for the homes in this study was 4.8 ach, which compares to a median of 5.2 ach for a group of homes built since 1992, and 8.6 ach for a group of homes built before 1987. Thus, new Californian homes are generally being built tighter, but not exceptionally tight, as are found in colder climate regions.

Home-to-Garage Air Leakage. A total of 65% of the homes did not meet the American Lung Association guideline for a home-to-garage negative pressure of at least -49 pascals (Pa) when the home is depressurized to -50 Pa with respect to the outdoors. In the three-home Pilot Study, tracer gas measurements indicated that between 4% and 11% of the garage sources entered the home. Thus, a substantial amount of air from attached garages, which often contain air contaminant sources such as vehicle fuel, exhaust fumes, gasoline-powered lawn equipment, solvents, oils, paints, and pesticides can enter the indoor air of the home.

Mechanically Supplied Outdoor Airflow Rates. A total of 64% of DOA systems failed to meet the requirements of the Energy Commission's new 2008 Building Energy Efficiency Standards. The very low outdoor air exchange rates for the DOA systems are a result of the combination of low outdoor airflow rates and short operating times. HRV systems performed much better. None of the HRV systems failed to meet the new 2008 Building Energy Efficiency Standards. These results show that, as encountered in this field study, HRV systems are a more effective outdoor air supply strategy than the DOA systems.

Intermittent mechanical outdoor air systems, such as DOA systems, cannot perform equivalently to continuous systems such as HRV systems with respect to controlling the short-term exposures to indoor air contaminants, especially if the cycle times are long (e.g., greater than two hours). The 2008 Building Energy Efficiency Standards, which were adopted after this study was completed, require a minimum operation time of one hour every 12 hours. During extended outdoor air ventilation off-times, intermittent ventilation systems allow for air contaminants with indoor sources to increase substantially, as compared to the increases that would occur with a continuous ventilation system. For some indoor air contaminants, such as those that cause irritation and/or odor, the effects are initiated by the immediate exposure to the indoor concentration rather than prolonged exposure to a concentration over a period of time. For such compounds, intermittent ventilation systems may not be sufficient for reducing indoor concentrations to acceptable levels.

Provided that DOA systems are equipped with fan cyclers with fan cycle times and outdoor airflow rates set to provide the required outdoor air ventilation, there is no reason that these systems cannot perform equivalently to continuous systems, such as HRV systems, with respect to controlling the long-term exposures to indoor air contaminants.

However, as noted above, intermittent mechanical outdoor air systems, such as DOA systems, cannot perform equivalently to continuous systems such as HRV systems with respect to controlling the short-term exposures to indoor air contaminants.

In addition, the increased outdoor air ventilation for intermittent ventilation systems, as required by the 2008 Building Energy Efficiency Standards and adopted from ASHRAE 62.2-2007, does not always provide equivalent long-term average indoor concentrations, especially for systems with long cycle times (e.g., 12 hours). The long-term average air contaminant concentrations can be substantially higher (e.g., 30%), which is important for health effects such as cancer and cardiovascular disease. The recent ASHRAE 62.2 2008 Addendum b, which has not been adopted by the California Building Energy Efficiency Standards, further reduces the outdoor air ventilation rates for intermittent residential mechanical systems, which translates into higher exposures to indoor air contaminants.

<u>Tracer Gas Measurements of Home Outdoor Air Exchange Rates</u>. The median 24-hour measurement was 0.26 ach, with a range of 0.09 ach to 5.3 ach. A total of 67% of the homes had outdoor air exchange rates below the minimum CBC code requirement of 0.35 ach. Thus, the relatively tight envelope construction, combined with the fact that many people never open their windows for ventilation, results in homes with low outdoor air exchange rates. The median two-week measurement of outdoor air exchange rates was generally close to the 24-hour median value.

<u>Indoor Air Contaminant Concentrations</u>. This study measured the 24-hour average concentration of 22 individual volatile organic compounds, including formaldehyde and acetaldehyde, and the 1-hour and 8-hour maximum average carbon monoxide concentrations. Also measured were the 24-hour average concentration of $PM_{2.5}$ particulate matter and nitrogen dioxide in the 29 homes of the Winter-North field session. The only indoor air contaminants that exceeded recommended non-cancer and non-reproductive toxicity guidelines were formaldehyde and $PM_{2.5}$. For formaldehyde, 98% of the homes exceeded the Chronic and 8-hour RELs of 9 $\mu g/m^3$, 59% exceeded the ARB indoor air guideline of 33 $\mu g/m^3$, and 28% exceeded the OEHHA Acute REL of 55 $\mu g/m^3$. For $PM_{2.5}$, only one home, with an indoor concentration of 36 $\mu g/m^3$, exceeded the EPA $PM_{2.5}$ 24-hour ambient air quality standard of 35 $\mu g/m^3$. Thus, most new homes had indoor concentrations of formaldehyde that exceeded recommended guidelines

<u>Volatile Organic Compound Proposition 65 Safe Harbor Levels</u>. For each of the seven volatile organic compounds with NSRLs for cancer, there were some homes that exceeded the indoor NSRL concentration. For formaldehyde and acetaldehyde, the percentage of homes exceeding the NSRL concentration were 100% and 92% respectively.

For the five other VOCs, the percentage of homes exceeding the NSRL concentration ranged from 8% for trichloromethane (chloroform) and tetrachloroethene to 63% for benzene. For the two volatile organic compounds with MADLs for reproductive toxicity, only the benzene MADL was exceeded. A total of 20% of the homes had indoor benzene concentrations that exceeded the calculated indoor MADL concentration. Thus, a substantial percentage of new homes have indoor concentrations that exceed recommended guidelines for cancer and/or reproductive toxicity.

Potential Sources of Indoor Air Contaminants. The primary source of the indoor concentrations of acetaldehyde and formaldehyde, which were the two air contaminants that most frequently exceed recommended guidelines, is believed to be composite wood products. While this study was not able to determine the extent to which formaldehyde-based resins were used in the composite wood identified in the homes, formaldehyde-based resins are the most common resins used in the production of composite wood products. The composite wood identified in these homes include particleboard that was used in 99% of the kitchen and bathroom cabinetry, as well as many pieces of furniture. Other sources of composite wood include plywood and oriented strand board in walls, subfloors, and attics, and medium density fiberboard in baseboards, window shades, interior doors, and window and door trims.

While composite wood products are believed to be the major indoor source of both formaldehyde and acetaldehyde, other indoor sources of both formaldehyde and acetaldehyde include combustion sources (e.g., tobacco smoking, cooking fireplaces, woodstoves), cellulose-based products such as acoustic ceiling tiles, and paints. Additional sources of formaldehyde include permanent-pressed fabrics and insulation made with urea formaldehyde resins.

In the few measurements that were made in this study of the emission rates of formaldehyde from FAUs, it does appear that in the summer, when attic temperatures can become elevated, that the FAU can transport formaldehyde into the home from either emissions of formaldehyde from fiberglass soundliner directly into the FAU airstream or from leakage of attic air with elevated formaldehyde concentrations into the return air of the FAU.

Potential sources of some VOCs were identified for homes with elevated indoor VOC concentrations. The following potential sources of indoor air contaminants are suggested from a comparison of the occupant activity logs and house characteristics with the indoor contaminant concentrations and emission rates; 1,4-dichlorobenzene and naphthalene from mothballs, d-limonene from furniture polish and cleaning chemicals, 2-butoxyethanol from anti-bacterial wipes, toluene from air fresheners, and tetrachloroethene from dry-cleaned clothes or drapes.

Objective 3. Determine occupant perceptions of, and satisfaction with, the IAQ in their homes.

A total of 28% of the households reported experiencing one or more of nine physical symptoms during the previous three weeks that they did not experience when they were away from the home. The three most frequently reported symptoms were nose/sinus congestion (19%), allergy symptoms (15%), and headache (13%). The three most frequently reported thermal comfort perceptions were “too cold” (19%), “too hot” (15%), and “too stagnant (not enough air movement)” (12%).Thus, a substantial percentage of occupants in new homes report experiencing physical symptoms or thermal discomfort.

The most frequently reported location where the homeowners reported mold or mildew was the bathroom, which was reported by 13% of the homeowners. The percentage of homeowners reporting mold or mildew at other locations ranged from 0.9% and 2.8%.

Objective 4. Examine the relationships among home ventilation characteristics, measured and perceived IAQ, and house and household characteristics.

Because of the low number of homeowners reporting IAQ related perceptions and observations, there are insufficient data to prepare statistically meaningful correlations with home and IAQ characteristics.

Statistical comparisons were conducted for indoor formaldehyde and acetaldehyde concentrations, outdoor air exchanges rates, and window usage. Formaldehyde and acetaldehyde were selected for these analyses, as these were the two air contaminants that most frequently exceeded recommended indoor concentration guidelines. The group comparisons consisted of homes in the north versus south regions, homes in summer versus winter seasons, and homes without mechanical outdoor air systems versus homes with either pure DOA or pure HRV outdoor air ventilation systems. Because of the small number of homes in the sample groups and the important seasonal and house-specific differences, these comparisons should only be considered as suggestive of differences. Multivariate analyses need to be conducted to further establish any differences between the groups.

Formaldehyde concentrations were found to be significantly higher in the following group comparisons:

- Non-mechanically ventilated North homes higher than South homes
- DOA homes higher than homes without mechanical outdoor air ventilation systems
- DOA homes higher than HRV homes

Acetaldehyde concentrations were found to be significantly higher in the following group comparisons:

- DOA homes higher than homes without mechanical outdoor air ventilation systems
- DOA homes higher than HRV homes

Window usage was found to be significantly higher in the following group comparisons:

- Summer homes higher than winter homes

Outdoor air exchange rates were found to be significantly higher in the following group comparisons:

- HRV homes higher than homes without mechanical outdoor air ventilation systems
- HRV homes higher than DOA homes

While the DOA homes generally had lower outdoor air exchange rates, and therefore higher indoor formaldehyde and acetaldehyde concentrations, as noted above, the poor performance of the DOA systems is a result of a lack of controls (e.g., fan cyclers) to ensure adequate fractional on-time of the FAU fan and a lack of proper sizing and balancing of the outdoor air duct to ensure sufficient outdoor airflow rate into the system when the FAU fan was operated.

Correlation analyses were also prepared for indoor formaldehyde and acetaldehyde concentrations with six home characteristics and four environmental conditions. For both formaldehyde and acetaldehyde concentrations, the outdoor air exchange rate was determined to have a significant inverse correlation. For formaldehyde concentrations, indoor air temperature was determined to have a significant correlation. These results indicate that as outdoor air exchange rates decrease or the indoor temperate increases, the indoor concentrations of formaldehyde increase.

An unexpected result was that there was a negative correlation for composite wood loading and acetaldehyde indoor concentrations and no significant correlation for composite wood loading and formaldehyde indoor concentrations, despite the knowledge that composite wood is an indoor emitter of both formaldehyde and acetaldehyde. This may be the result of incompleteness of the recovery of this variable in the field from the visible inspection by the field team. Composite wood could not always be accurately identified because of coverings by laminate or paint. In addition, the inspectors only estimated the square footage of composite wood from furniture and cabinetry. Other substantial amounts of composite wood loading that are common in many of these homes, but are difficult to quantify in the limited time available to the inspectors, include plywood and oriented strand board in walls, subfloors, and attics, and medium density fiberboard in baseboards, window shades, interior doors, and window and door trims. Also, the inspectors estimated the areas of composite wood without separately distinguishing those areas that were exposed and those areas that were covered with laminate.

The variance introduced by the impact of outdoor air exchange rates upon the indoor concentrations of formaldehyde and acetaldehyde may also be contributing to the lack of an observed significant positive correlation between composite wood loading and the indoor concentrations of formaldehyde and acetaldehyde.

Our multi-day measurements in four homes indicated a modest variation in the outdoor air exchange rates (i.e., an average relative standard deviation of 0.19) and indoor air contaminant concentrations (i.e., an average relative standard deviation of 0.34). Our multi-season measurements in four homes indicated a substantially larger variation in the outdoor air exchange rates (i.e., an average relative standard deviation of 0.67, which is 3.5 times higher than the multi-day variation) and indoor air contaminant concentrations (i.e., an average relative standard deviation of 0.60, which is 1.8 times higher than the multi-day variation).

Thus, the larger variations in the indoor air contaminant concentrations in the multi-season homes appears to be the combination of larger variations in the outdoor air exchange rates and the indoor air contaminant emission rates.

Objective 5. Identify the incentives and barriers that influence people's use of windows, doors, and mechanical ventilation devices for adequate air exchange.

Of the homeowners with mechanical outdoor air systems (i.e., DOA or HRV systems, not nighttime cooling systems, evaporative cooling systems, or window fans):

- 78% stated that the operation of the system was explained to them when they bought or moved into the house
- 63% responded that they understood how the system works
- 83% stated that they felt that they understood how to operate the system properly

A total of 91% stated they chose the system because it came with the house and the things they liked most about the system were: "Fresh air" (52%), "Quiet" (48%), and "Reduced concern about indoor air quality" (26%). The things they liked least about the system were: "Not effective" (32%), "Too drafty" (26%), and "Too noisy" (26%).

Objective 6. Identify the incentives and barriers related to people's purchases and practices that improve IAQ, such as the use of low-emitting building materials and improved air filters.

A total of 24% of the 105 respondents stated "none" in response to the question "What special measures or choices have you or the builder taken to improve the quality of the air in your home?". The four most frequent responses to improvements undertaken were: "Hard flooring instead of carpeting" (33%), "Carbon monoxide alarm" (28%), "High efficiency vacuum cleaner with special features such as filters to trap more particles" (27%), and "Upgrade my central air filter" (25%).

The following summarizes the main conclusions from this study of new single family homes built in California between 2002–2004.

1. Many homeowners never open their windows or doors especially in the winter months.

2. New homes in California are built relatively tight, such that natural air infiltration rates through the building envelope can be very low (e.g., 0.1 ach).

3. In new homes with low outdoor air exchange rates, indoor concentrations of air contaminants with indoor sources, such as formaldehyde and some other volatile organic compounds, can become substantially elevated and exceed recommended exposure guidelines.

4. DOA mechanical outdoor air ventilation systems generally did not perform well as a result of the low outdoor airflow rates and short operating times. A total of 64% of DOA systems failed to meet the ASHRAE 62.2-2007 guideline for residential ventilation, which is referenced in the Energy Commission's new 2008 Building Energy Efficiency Standards.

5. HRV mechanical outdoor air ventilation systems performed much better than DOA systems. All of HRV systems met the Energy Commission's new 2008 Building Energy Efficiency Standards

4.3 Recommendations

The research team recommends the following, based on the study results:

1. Consideration should be given to installing mechanical outdoor air ventilation systems in new single-family residences to provide a dependable and continuous supply of outdoor air to the residence for the purpose of controlling indoor sources of air contaminants. The reason for this recommendation is that new homes are built relatively tight, and many people do not use their windows for outdoor ventilation, which results in homes with low outdoor air exchange rates and elevated concentrations of contaminants with indoor sources. To this end, the Energy Commission adopted the 2008 Building Energy Efficiency Standards, which will require all new low-rise residential buildings to have a mechanical outdoor air ventilation system.

2. Consideration should be given to regulating the emissions of air contaminants from building materials. The Air Resources Board approved a regulation in 2007 to limit formaldehyde emissions from composite wood products, “Airborne Toxic Control Measure to Reduce Formaldehyde Emissions from Composite Wood Products,” which was approved by the Office of Administrative Law on April 18, 2008, with an implementation date of January 1, 2009.

3. Given the relatively high frequency that indoor formaldehyde concentrations exceeded recommended exposure guidelines, and the fact that formaldehyde is a known human carcinogen, consideration should be given to conducting studies focused on quantifying the emission rates of formaldehyde from all potential indoor sources (e.g., building materials, furnishings, consumer products) and based on this research, developing regulations to reduce indoor formaldehyde emissions.

4. Outreach to public and professional groups should be increased regarding the need to reduce indoor formaldehyde concentrations in existing homes by sealing exposed composite wood surfaces, selecting low-emission furniture, improving outdoor air ventilation in the home, and controlling indoor humidity.

5. Multivariate analyses of the data collected in this study should be conducted to further develop the understanding of the relationships between indoor air contaminant concentrations (e.g., homes with unusually high or low concentrations), indoor sources, ventilation, season, and other major sources of variance. The analyses conducted as part of this report were bivariate analyses, which established statistical associations but not necessarily cause-and-effect relations, as other factors may be found to be equally or more important when analyzed together in multivariate analyses. Multivariate analyses of indoor contaminant concentrations are needed in order to adjust the preliminary estimates from this study by accounting for home volume, outdoor air exchange rate, and other major sources of variance. Additional sources of indoor formaldehyde emissions should be considered, such as the presence of new furniture, duct leakage for potential attic sources, gas stove or fireplace usage, and the presence of alkenes in the outdoor ozone season.

6. Construction of a statewide population-weighted exposure assessment from the data collected in this field study should be performed to better understand the air contaminant source and ventilation characteristics of new homes. While the UCB mail survey sample, upon which this study’s sample selection was largely but not entirely based, was a stratified random sample, the results in this study have not been weighted to adjust for that stratification or other selection factors.

7. Additional studies of indoor air quality and ventilation with diurnal wind speed and temperature swings should be conducted to examine the significance of nighttime cooling by natural or mechanical means.

8. Further studies in additional homes with mechanical outdoor air ventilation systems should be conducted to confirm the findings identified in this study and with consideration for other building factors. Both installation and field performance of the mechanical outdoor air ventilation systems should be evaluated.

9. Consideration should be given to revising the 2008 Building Energy Efficiency Standards and the companion Residential Compliance Manual, which refer to ASHRAE Standard 62.2-2007, to fix the error in the tabulated ventilation effectiveness values for mechanical outdoor air ventilation systems with intermittent fan operation. The ventilation effectiveness values currently do not provide intermittent ventilation systems enough additional ventilation to provide long-term average concentrations of air contaminants with indoor sources that are equivalent to those for constant ventilation systems. In addition, consider reducing the maximum cycle time of intermittent ventilation systems from the current 12-hour maximum to 1–2 hours so that the short-term exposures to air contaminants with indoor sources are not substantially higher than those with constant ventilation systems.

10. Research should be conducted on exhaust-only ventilation systems, which were not encountered in this study. These systems are relatively low in cost and likely to be used in many homes to meet the new 2008 Building Energy Efficiency Standards requirements in California. However, exhaust-only systems may not provide good distribution of the outdoor air and may increase the infiltration of some air contaminants as a result of depressurization of the air in the home.

11. Home builders should be educated about the importance of conveying to homeowners the need for outdoor air ventilation in homes and how the ventilation systems operate, as well as the importance of designing systems that are easy for homeowners to maintain. In addition, consideration should be given to creating an easy-to-read short fact sheet that can be distributed to the public regarding residential ventilation systems and the importance of the operation and maintenance of these systems to indoor air quality.

12. Research should be conducted to investigate residential exposures to ozone-initiated reaction products (e.g., formaldehyde and other aldehydes and ultrafine particles) that are formed when ozone reacts with contaminants, such as d-limonene, which is emitted by many air freshener and cleaning products as well as by some orange oil termite treatments. The database for this project contains

important information for such research, including d-limonene concentrations, outdoor air exchange rates, air cleaners that generate ozone, and formaldehyde and other aldehyde concentrations.

4.4 Benefits to California

This was the first large field study of window use, outdoor air ventilation rates, and indoor air contaminants in new California homes. The data from this study were immediately useful for the California Energy Commission in guiding the development of building design standards that protect indoor air quality and comfort in California homes, and for the California Air Resources Board to improve exposure assessments of indoor and outdoor air contaminants. In particular, the Energy Commission used the study results as a scientific basis to revise the state's building energy efficiency standards in order to provide more healthful, energy-efficient homes in California. The study results will also improve ARB's ability to identify current sources of indoor air contaminants, to assess Californians current exposure to measured toxic air contaminants, and to recommend effective strategies for reducing indoor air pollution.

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6.0 Glossary of Terms, Abbreviations, and Symbols

A_{floor}	Floor Area
ACH	Air Changes per Hour
ACH_{50}	Air Changes per Hour at 50 pascals
ALA	American Lung Association
APT	Automated Pressure Testing
ARB	California Air Resources Board
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
ASTM	American Society for Testing and Materials
ATCM	Airborne Toxics Control Measure
C_i	Indoor Concentration
$C_{i\text{-}pdch}$	Concentration of PDCH garage tracer in the home Indoor air
C_o	Outdoor Concentration
C_{ra}	Concentration in the FAU Return Air at the return air inlet
C_{sa}	Concentration in the FAU Supply Air at the supply air diffuser
CATS	Capillary Adsorption Tube Sampler
CBC	California Building Code
CFI	Central Fan Integrated mechanical ventilation system (same as DOA)
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DNPH	Dinitrophenylhydrazine
DOA	Ducted Outdoor Air mechanical ventilation system (same as CFI)
DOE	Department of Energy
E	Emission Rate
E_{fau}	Emission rate from the FAU
$E_{g\text{-}pdch}$	emission of PDCH garage tracer into garage
$E_{h/g}$	Percentage of Garage Emissions entering Home
E_{home}	Emission rate into the home
E_v	Emission rate into home-volume specific
EC	Evaporative Cooling mechanical ventilation system
EPA	Environmental Protection Agency
EqLA	Equivalent Leakage Area
FAU	Forced Air Unit
HEPA	High Efficiency Particulate Air Filter
HRV	Heat Recovery Ventilator mechanical ventilation system
HVAC	Heating, Ventilating, and Air Conditioning
HWPW	Hardwood Plywood
IAQ	Indoor Air Quality
IARC	International Agency for Research on Cancer

K-S	Kolmogorov-Smirnov
LBNL	Lawrence Berkeley National laboratory
MADL	Maximum Allowable Dose Levels
MDF	Medium Density Fiberboard
MDL	Method Detection Limit
MERV	Minimum Efficiency Reporting Value
MMDL	Method Mass Detection Limit
MADL	Maximum Allowable Dose Levels
MVDL	Method Volume Detection Limit
N_{br}	Number of Bedrooms
NDIR	Non-Dispersive Infrared Spectrophotometry
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and technology
NSRL	No Significant Risk Levels
OEHHA	Office of Environmental Health Hazard Assessment
OSB	Oriented Strand Board
Pa	Pascals
PB	Particleboard
PFT	Perfluorocarbon Tracer
PIER	Public Interest Energy Research
$PM_{2.5}$	Particulate Matter Less Than 2.5 µm Aerodynamic Diameter
p-PDCH	para-Perfluorodimethylcyclohexane
PMCH	Perfluoromethylcyclohexane
PPB	Parts per Million by volume
PPM	Parts per Billion by volume
Q_f	Required intermittent mechanical outdoor airflow rate
Q_{fau}	Airflow rate of the FAU
Q_r	Required continuous mechanical outdoor airflow rate
QA/QC	Quality Assurance / Quality Control Plan
RD&D	Research, Development, and Demonstration
RAD	Return Air Damper nighttime cooling ventilation system
REL	Reference Exposure Level
SIP	Structural Insulated Panels
SLA	Specific Leakage Area
SOP	Standard Operating Procedures
UCB	University of California at Berkeley
V	Volume of indoor air
VOC	Volatile Organic Compound
WDF	Window Fan
WHF	Whole House Fan nighttime cooling ventilation system

ε	Ventilation effectiveness factor for intermittent ventilation
f	Fractional on-time of intermittent ventilation system
λ_{pft}	Outdoor air exchange rate determined from PFT measurement